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ADVANCED SPACECRAFT VALVE TECHNOLOGY COMPILATION

VOLUME II
NONMECHANICAL CONTROLS

Prepared for

THE JET PROPULSION LABORATORY
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Contract NAS 7-717

TRW
SYSTEMS GROUP

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FOREWORD

This compilation was prepared by TRW Systems Group, Redondo Beach, California. The compilation represents the results of work undertaken on a series of programs with the objectives of advancing the art of valve technology used on liquid chemical propulsion spacecraft engines. The compilation is published in two volumes. Volume I reports the results of the work accomplished on the Mechanical Controls (Moving Parts) study including instrumentation and technology support investigations. This volume (Volume II) reports on the Nonmechanical Controls (No Moving Parts) and represents those controls having no moving or sliding parts including fluidics and electro-fluid modulation devices. The program was originated and managed by the Jet Propulsion Laboratory under the technical direction of Mr. Louis R. Toth. The NASA Program Manager was Mr. Frank E. Compitello, Code RPL, Office of Advanced Research and Technology.

The work performed on the program was accomplished by TRW Systems Group, Science and Technology Division, Technology Laboratory. Mr. R. J. Salvinski of the Applied Technology Department was the Program Manager. Mr. C. Mangion of the Applied Technology Department was the major contributor and author of Volume II.

INTRODUCTION

The purpose of the Advanced Valve Technology Compilation is to document in a single source the results of the efforts expended during the past several years on advancing the state of the art of valves and controls used on liquid chemical rocket engines for manned and unmanned space exploration vehicles. The controls studied were those used with earth and space storables and cryogenic propellants at pressures to 1000 psia and operate for periods of up to ten years. The ten year requirement was considered in conjunction with missions beyond Jupiter to the outer planets, Saturn, Uranus, Neptune and Pluto. Considerations were given to electrical, pneumatic (hot and cold gas) and hydraulic actuated valves and actuator concepts.

Functional requirements for valves and actuators include zero leakage, service life (1,000 to 10,000 cycles), low weight, minimum size, minimum pressure drop and minimum power consumption. Environmental parametric requirements include zero gravity, radiation, shock and vibration, sterilization (300°F temperature soak, and/or ethylene oxide sterilant), thermal shock, thermal cycling, vacuum and other effects anticipated by operating for periods of two, five and ten years in the space and planetary environments. Thrust levels used for specific valve and control applications were 50 lb, 200 lb and 1000 lb.

Two broad classes of valve and controls technology are emerging which find application to controlling the flow of gaseous pressurants and liquid propellants. The two classes of flow are: 1) Mechanical Controls (moving parts) and 2) Nonmechanical Controls (no moving parts).

The first class includes those valves represented by mechanical elements such as diaphragms, seals, hydraulic, pneumatic and electrical actuators. The second class represents a group of fluid controls that have no sliding or moving parts and include fluidics and electric and magnetic fluid interaction devices.

The valve compilation is produced in two volumes, Volume I Mechanical Controls and Volume II Nonmechanical Controls. The compilation is divided into eight sections which make up the two volumes.

Volume I - Mechanical Controls

- 1.0 Introduction
- 2.0 Operational, Functional and Environmental Considerations
- 3.0 Materials
- 4.0 Valves
- 5.0 Leakage and Seal Technology
- 6.0 Valve Actuators
- 7.0 Instrumentation and Measurement

Volume II - Nonmechanical Controls

- 8.0 Fluidics

Fluidics is a new technology which is based on the utilization of fluid dynamic phenomena to performing sensing, signal amplification and processing, and power amplification in control functions without moving parts. Hybrid devices based on fluidic principles as well as fluidic components are being considered for spacecraft liquid propulsion application because of the unique capabilities they offer. The elimination or minimization of moving mechanical parts allows the design of more rugged components, with improved reliability, that can be fabricated from a wide range of materials. These characteristics coupled with fluid operation results in components that are insensitive to extreme temperature, radiation, vibration, and shock environments.

The major source of the material used in compiling the Volume II compilation were taken from the following references:

1. Advanced Valve Technology, Interim Report No. 06641-6004-R000, November 1966, Contract NAS 7-436.

2. Advanced Valve Technology, Interim Report No. 06641-6014-R000, Volume I, Spacecraft Valve Technology, Volume II, Materials Compatibility and Liquid Propellant Study, November 1967, Contract NAS 7-436.

3. Advanced Valve Technology, Interim Report No. 06641-6023-R000, Volume II, Nonmechanical Controls, January 1969, Contract NAS 7-436.

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8.0 FLUIDICS

8.1 INTRODUCTION

The Fluidics Section summarizes nonmechanical control studies which were concerned with the application of fluidics technology to liquid chemical propulsion systems. These studies were performed with the primary objective of advancing the art of propulsion system fluid controls through analysis, design, and feasibility demonstrations. The major tasks which were undertaken to meet these objectives include:

1. Comprehensive literature and patent searches and a survey of the leading government agencies and companies involved with fluidics.

2. A review of the properties and parameters of fluid mechanics pertaining to fluidics and the definition of accepted terminology and symbology.

3. A study of the operating principles, configurations, and applications of the basic fluidic components and consideration of performance relative to propellants, specific functional parameters and the space environment.

4. Application studies and investigations of new concepts.

8.1.1 Definition and Role of Fluidics

A fluidic system is one in which sensing, control, signal processing or amplification functions are performed through the use of fluid dynamic phenomena, i.e., no moving mechanical parts (Reference 1). The role of fluidics in the evolution of fluid systems can be compared to the role of electronics in the evolution of electronic systems. Common usage defines a fluid system with one fluidic device as a fluidics system just as an electrical system with one electronic device is called an electronics system.

Although fluid power control devices and systems have been used for many years in a wide variety of applications, heretofore, they could not be employed effectively at low power levels because of the complexity and relative unreliability of miniaturized mechanical devices. Therefore, readily available electrical and electronic devices and circuits were preferred for low power level control functions such as sensing, signal transmission, switching, and amplification. With the growing availability of a wide variety of fluidic control elements, power elements, and interface transducers, a new generation of fluid control systems are being developed which offer improved reliability potential through the elimination of moving mechanical parts. The role of fluidics is not limited to these low power level control functions but encompasses the entire range of fluid power and propellant feed systems.

8.1.2 Advantages and Limitations of Fluidics

Fluidics offers unique capabilities which are leading to a new generation of valves and controls for aerospace systems. Practically any fluid can be used and some fluidic elements will operate equally well on gases or liquids or both. The primary advantage fluidics offers occurs when fluids are used for performing all functions, and components such as sensors, logic devices, and amplifiers can be conveniently coupled together directly. Such a system eliminates the need for interface devices, that is, the transducers between the electrical and fluid portions of the system. This simplifying characteristic as well as a wide range of available fabrication materials, including high temperature alloys and ceramics, makes fluidic systems capable of operating in extreme temperature, radiation, vibration, and shock environments. An obvious advantage is that there are no moving parts to seize or wear out.

8.1.3 The Basis for Fluidics

Most fluidic elements utilize fluid dynamic phenomena which has been know for many years. This includes wall attachment (Coanda Effect), jet deflection, turbulent mixing, momentum exchange, vortex generation, turbulent diffusion, boundary layer separation, and the transition from laminar to turbulent flow. Wall attachment, for example, is observed when water spills over the edge, reattaches, and runs down the side of a tipped glass. The deflection of a rocket engine exhaust flow by the perpendicular injection of a secondary fluid involves a more complex combination of jet deflection, momentum exchange and boundary layer separation. The jet pump is another example of the application of fluidic principles.

The initial recognition of fluidics as a separate technology was preceded by several significant events. In 1904, Prandtl, while investigating flow separation in a wide angle diffuser discovered that flow separation could be varied by applying suction at the boundary layer of the diffuser (Reference 2). By installing control ports at each side of the diffuser, he found that when suction was applied to one side of the diffuser, the discharge fluid would adhere to that side (Figure 8-1). When suction was applied at the control ports on both sides of the diffuser, the discharge flow expanded and filled the entire diffuser. Prandtl could have made the first logic element by installing an output duct on each side of the diffuser.

In 1916, Tesla invented the valvular conduit (Figure 8-2) which has been acclaimed as the first pure fluid device with no moving parts. This device is actually a fluidic diode which offers low resistance to flow in one direction and a high resistance in the opposite direction (Reference 3).

During the 1930's, Henrie Coanda discovered what has been called the Coanda Effect, which is of major importance to fluidic technology. Coanda observed that when a free jet was introduced near an adjacent curved or flat plate, the jet would adhere to the plate and follow the plate, even though the new flow path diverged as much as 45 degrees from the original flow direction. This phenomena is explained by the fact that the emerging jet stream entrains molecules of fluid in adjacent space due to the large velocity gradient at the edge of the jet (Figure 8-3). Near the adjacent plate the entrained fluid is not easily replaced whereas on the opposite side of the jet, entrained fluid is easily replaced by ambient fluid. This condition results in the formation of a low pressure bubble or vortex and the development of a transverse pressure gradient across the jet which bends the jet toward and eventually against the adjacent plate.

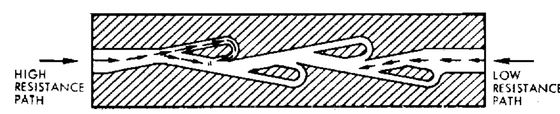


Figure 8-2. Tesla's Valvular Conduit

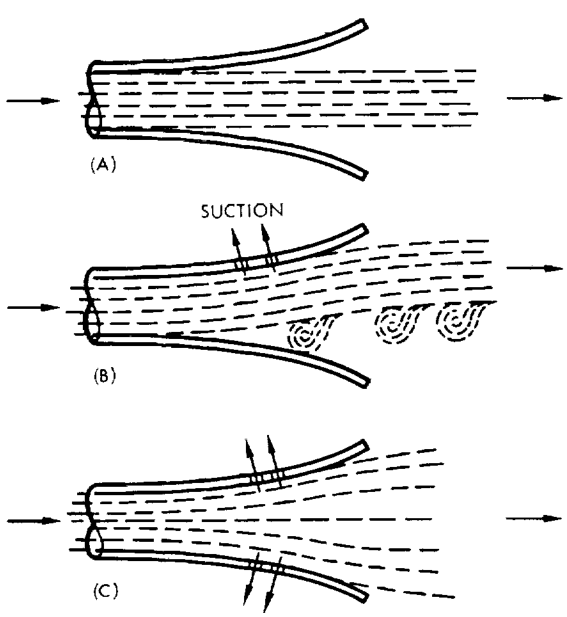


Figure 8-1. Prandtl Diffuser

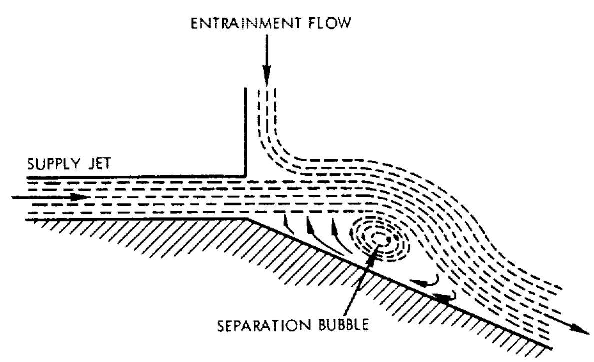


Figure 8-3. The Coanda Effect

8.2 FLUIDIC STANDARDS

The fluidic terminology, nomenclature, graphic symbology, and definitions used during this study are based primarily on MIL Standard 1306 (Reference 4) and SAE ARP 993A, Fluidic Technology (Reference 1).

8.2.1 Fundamental Theory

The important properties and parameters of fluid mechanics pertaining to fluidics (in particular, fluid pressure, fluid flow, and fluid resistance) are given a general treatment in References 5 and 6 and a more detailed treatment in Reference 7. Section 3.0, Fluid Mechanics, of the Aerospace Fluid Component Designers Handbook (Reference 8) provides an excellent definition of the fundamental theory and equations of fluid flow.

8.2.2 Units, Dimensions, and Nomenclature

MIL Standard 1306 (Reference 4) defines the basic quantities in both the internation system (SI) and english (Standard) units and recommends that all current and future work should be documented and reported in SI units. The basic quantities used in this study along with the accepted symbols of both the SI and english units are tabulated in Appendix 8A. This information was adapted from References 4 and 8.

8.2.3 Terminology

Terms common to fluidics are defined in both MIL Standard 1306 and SAE ARP 993A. Appendix 8B contains a terminology list extracted from these sources.

8.2.4 Graphical Symbology

The first set of symbols for fluidic circuitry was presented by General Electric Company personnel at the October 1962 Fluid Amplification Symposium held at the Harry Diamond Laboratories, Washington, D. C. (References 9 and 10). Since then the National Fluid Power Association (NFPA) and the Fluidics Panel of the Society of Automotive Engineers (SAE) Committee A-6 (Aerospace Fluid Power and Control Technology) have done a great deal of work in defining fluidic standards. Both organizations are in agreement with regards to graphical symbology. Appendix 8C lists the accepted graphical symbols which are defined in both SAE ARP 993A (Reference 1) and MIL Standard 1306 (Reference 4).

8.3 SURVEYS

The nonmechanical control studies were supplemented by searches and agency interviews to determine the extent of existing data and to evaluate the major applications and the problem areas. Most of this information is covered in other sections of this report. The fluidic literature and patent bibliographies and the fluidic subject index prepared from the survey material are defined below and available in Reference 11.

8.3.1 Fluidic Literature Bibliography

This bibliography (Reference 11) was compiled from a wide variety of government, domestic, and foreign sources by the Technical Information Center of TRW Systems Group. Entries were restricted to fluidic (no moving part) devices, moving part logic elements, and the supporting technology. The lists are comprehensive from about mid 1965 to date and important references were picked up back to about 1962. Each of the 1,034 entries is listed in alphabetical order by author or by the publishing agency when no author was given.

The earlier literature concentrated primarily on fluidic components and the fluid dynamic phenomena relevant to fluidics. The current trend in the literature is toward systems and applications. Consideration is also being given to the scaling of elements and the effects of environmental extremes on element performance. Some interest is also evolving in hydraulic fluidics and fluidic to hydraulic interfaces. A primary need is seen for fluidic sensors and interfaces to engender the use of analog and hybrid fluidic controls. Formal analysis has made some inroads at the component level but no significant system effort was found. Approximate methods of systematic design are being used which take advantage of the systems design methods already developed in the fields of mechanics, electronics, and hydraulics. The user problems most prominent are repeatability among elements and circuit interconnections.

8.3.2 Fluidic Patent Bibliography

This bibliography (Reference 11) was compiled by the TRW Systems Patent Office through a search of the United States Patent Files. It contains 416 entires which are arranged sequentially by patent number. The listings are comprehensive from 1961 to date with a few isolated entries dating back to 1920. The patent search was limited to fluidic (no moving part) devices and the supporting technology.

A significant number of the listed patents are on digital elements and circuits. This includes basic digital devices and the means of optimizing element performance. The digital circuit patents encompass comparison matrices, shift registers, multi-state adders, universal registers, binary counters and non-destructive readout memory and include a calculating machine and a digital computer. Analog fluidic elements, sensors, and transducers of all types were also patented. In the analog area primary emphasis was seen in summing and integrating circuits. Sensors included rate, temperature, angular velocity, acceleration, and attitude measuring devices. Several electrical to fluidic transducers were evident, primarily acoustically driven types. Power elements including diverter valves, pressure regulators, and an attitude control thruster were also patented. Prominent among the many applications patented were turbine speed controls, respirators, carburetors, timers, and a digital actuator.

8.3.3 Fluidic Subject Index

A fluidic subject index (Reference 11) was organized so that the fluidic literature and patent bibliographies could be used effectively in obtaining information in a specific area of interest. The categories listed below were selected.

I	Capabilities
II	Commercial Applications
III	Aerospace Applications
IV	Propulsion Applications
V	Basic Fluid Flow
VI	Digital Components
VII	Analog Components
VIII	Valves and Power Elements
IX	Passive Elements and Interconnects
X	Sensors and Interface Devices
XI	Pneumatic Logic - Moving Parts
XII	Digital Systems
XIII	Analog Systems and Frequency Modulation
XIV	Hybrid Systems
XV	Component Performance
XVI	Analysis and Design
XVII	Instrumentation and Test
XVIII	Fabrication
XIX	Symposia, Bibliographies and Books

8.4 FLUIDICS STATE OF THE ART

Fluidic devices are available to perform a wide variety of control circuit functions. An understanding of the principles of operation, performance characteristics, and limitations is essential to the successful application of these devices and to the analysis, design, and test of circuits. The various fluid interaction phenomena that form the basis of fluidic technology are discussed and related to state of the art fluidic devices. Component performance is summarized as well as expected performance gains in the next 5 years. Methods of fabrication, materials, and associated test equipment are also covered.

8.4.1 Component Rating Analysis Chart

The state of the art of basic fluidic devices and interface elements are summarized in Table 8-1 relative to compatibility, functional parameters and the space environment. This chart presents ratings which are estimated based on information from various sources including the literature and patent searches, agency interviews, in-house evaluations, and performance analyses. Aerojet-General Report NASA CR-294, "Engine Operating Problems in Space, The Space Environment," was used as the source of data on the space environment.

Reliability ratings as assigned to the various combinations of fluidic components, propellants, and parameters are defined as follows:

Rating	Definition
1	Poor - a serious problem exists for which there is no satisfactory solution
2	Fair - a problem exists, but a remedy may be available
3	Satisfactory - i.e., within the state of the art
U	Information upon which to make a judgment is unavailable
NA	Combination is not applicable

8.4.2 Basic Device Phenomena

Most fluidic devices can be characterized by at least four basic functional parts: a supply port, an output port, one or more control ports and an interaction region (Figure 8-4). These parts have been respectively compared to the cathode, plate, control grid, and interelectrode region in a vacuum tube. The supply jet (fluid stream) in the fluidic device is introduced into the interaction region and directed toward the output port or receiver. The degree of pressure and flow recovery in the receiver is influenced by the details of the device configuration. Control flow is

RATING CHARACTERISTICS:

1 - POOR
2 - FAIR
3 - GOOD
U - UNAVAILABLE INFORMATION

APPLICATION DESIGNATIONS:

DC - DIGITAL CONTROL
PC - PROPORTIONAL CONTROL
PM - PRESSURE MODUCATION
FM - FLOW MODULATION

NOTES:

(a) LIQUIFIED PETROLEUM GAS - BUTENE, ETHYLENE, METHANE, PROPANE
(b) FLOX IS ALSO CONSIDERED A SPACE STORABLE

			PERFORMANCE WITH PROPELLANTS																								
			GASES								EARTH STORABLES							SPACE STORABLES											
APPLICATION			HYDROGEN	HELIUM	NITROGEN	OXYGEN	ARGON	CO_2	PROPELLANT BOILOFF	COMBUSTION PRODUCTS TO 1500°F	MON 10	NITROGEN TETROXIDE	AEROZINE 50	HYDRAZINE	MONOMETHYLHYDRAZINE	PENTABORANE	UDMH	CHLORINE PENTAFLUORIDE	CHLORINE TRIFLUORIDE	NITROGEN TRIFLUORIDE	NITRYL FLUORIDE	OXYGEN DIFLUORIDE	PERCHLORYL FLUORIDE	TETRAFLUOROHYDRAZINE	AMMONIA	DIBORANE	HYBALINE A5	LPG[a]
DC	DIGITAL DEVICES	WALL ATTACHMENT - VENTED	3	3	3	3	3	3	3	3	2	2	3	3	3	3	3	2	2	2	2	2	2	2	3	3	U	2
DC, FM		WALL ATTACHMENT - CLOSED	3	3	3	3	3	3	3	3	2	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
DC		TURBULENCE	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	U	2
DC, FM		INDUCTION	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	U	2
DC		EDGETONE	3	3	3	3	3	3	2	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	U	2
DC		FOCUSED JET	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
PC, PM, FM	PROPORTIONAL DEVICES	STREAM INTERACTION	3	3	3	3	3	3	3	3	2	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	U	2
ALL		VORTEX AMPLIFIER	3	3	3	3	3	3	3	3	2	2	3	3	3	2	3	2	2	2	2	2	2	2	2	2	U	2
ALL		VORTEX VALVE	3	3	3	3	3	3	3	3	2	2	3	3	3	2	3	2	2	2	3	2	2	2	2	2	U	2
PC, PM, FM		VENTED JET	3	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	U	2
DC, FM		FLOW DIVERTER	3	3	3	3	3	3	2	2	2	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
PC, PM, FM		BOUNDARY LAYER	3	3	3	2	2	2	2	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2
PC, PM, DC		IMPACT MODULATOR	3	3	3	3	3	3	2	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	2
PC, FM		THROAT INJECTION	3	3	3	3	2	2	2	3	2	3	3	3	3	2	3	2	2	2	2	2	2	2	2	2	2	2
PC, PM, DC																												
DC, PC	PASSIVE ELEMENTS	ORIFICE	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1-2	2	1-2	2	2	2	2	2	2	3	3
DC, PC		LAMINAR RESISTOR	3	3	3	3	2	2	2	2	2	3	3	3	3	3	3	1-2	2	1-2	2	2	2	1-2	2	1-2	3	3
PC		INDUCTOR	2	2	3	2	2	2	2	2	2	3	3	3	3	3	3	1-2	2	1-2	2	2	2	1-2	2	1-2	3	3
PC, DC		CAPACITOR	3	3		3	3	3	2	2	2	3	3	2	2	3	2	2	2	2	3	2	2	2	2	2	2	3
PC, DC		DIODE	3	3	3	3	3	3	3	2	2	2	3	3	3	2	3	2	2	2	3	2	2	2	2	2	U	2
DC, PC	INTERFACE DEVICES	ELECTRICAL TO FLUID	3	3	3	2	2	2	2	U	2	2	2	2	2	2	2	1-2	1-2	1-2	2	2	2	1-2	2	1-2	2	2
DC, PC		FLUID TO ELECTRICAL	2	2	2	2	2	2	1	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
DC, PC		MECHANICAL TO FLUID	3	3	3	2	2	2	U	U	2	2	3	3	2	2	2	U	U	U	U	U	U	U	U	2	2	2
DC, PC		FLUID TO MECHANICAL	3	3	3	2	2	2	U	U	2	2	3	3	2	2	2	U	U	U	U	U	U	U	U	2	2	2
DC, PC		PRESSURE SENSOR	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	U	U	U	U	U	U	U	U	2	2	2
DC, PC		TEMPERATURE SENSOR	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	U	U	U	U	U	U	U	U	2	2	2
DC, PC		FLOW SENSOR	3	3	3	3	3	3	3	3	2	3	3	3	3	2	3	U	U	U	U	U	U	U	U	2	U	2

HARD CRYOGENICS: FLOX[b] (80% LF_2, 20% LO_2)	LIQUID FLUORINE	LIQUID OXYGEN	LIQUID HYDROGEN	METALLIZED GELS: N_2H_4	UDMH	MMH	NON-METALLIZED GELS: N_2O_4	ClF_3	MAF-MIXED AMINE FUELS	FUNCTIONAL PARAMETERS: TEMPERATURE - HIGH TO 1500°F	TEMPERATURE 1500°F TO 2500°F	TEMPERATURE - LOW TO (-) 420°F	PRESSURE - LOW TO 10 PSIA	PRESSURE TO 100 PSIA	PRESSURE TO 1000 PSIA	GAS PRESSURE TO 5000 PSIA	TIME RESPONSE - GASES 1500 CPS	TIME RESPONSE - LIQUIDS > 1000 CPS	VIBRATION AND SHOCK	POWER REQUIREMENTS	OPERATING LIFE > 10^6 CYCLES	CONTAMINATION	LEAKAGE (NOT VENTED) > 10^{-7} SCCS He	STERILIZATION (300°F) FOR 60 HRS - 6 CYCLES)	SPACE MAINTENANCE	SIGNAL TO NOISE RATIO > 200	ENVIRONMENT: ON BOARD NUCLEAR POWER SOURCES	SPACE RADIATION: VAN ALLEN BELT	SOLAR FLARE	INDUCED BREMSTRAHLUNG	VACUUM	ZERO G	METEOROIDS	PROD OF COMBUSTION (TURN AROUND)
2	2	2	3	1	1	1	1	1	1	3	2	3	3	3	2	1	3	2	3	2	3	2-3	3	3	U	2	3	3	3	3	2	3	3	3
2	2	2	3	2	2	2	2	2	2	3	2	2-3	3	3	2-3	2	2	2	3	2	3	3	3	3	U	2	3	3	3	3	2	3	3	3
2	2	2	2	1	1	1	1	1	1	2	1	2	2	1	1	1	1	1	2	3	2	1	1	3	U	1	3	3	2	3	1	3	2	3
1	2	2	2	1	1	1	2	2	2	2	2	2	3	3	2	1	1-2	1	2	2	3	2	2	3	U	2	3	3	3	3	1	3	3	3
1	1	1	2	1	1	1	1	1	1	1	1	1	3	3	2	1	3	2	1	2	2	2	2	3	U	1	2	3	2	2	1	3	2	2
2	2	2	2	1	1	1	1	1	1	2	2	2	3	2	1	1	2	2	2	1	3	2	2	3	U	1	3	3	3	3	1	3	3	3
2	2	2	3	1	1	1	1	1	1	2	1	2	3	3	1	1	2	2	2	2	3	2	3	3	U	3	3	3	3	3	1	3	3	3
2	2	2	3	1-2	1-2	1-2	1-2	1-2	1-2	3	3	2	3	3	2	2	2	1	3	2	3	3	3	3	U	1	3	3	3	3	2	3	3	3
2	2	3	3	2	2	2	2	2	2	3	3	3	3	3	3	3	2	2	3	2	3	3	3	3	U	2	3	3	3	3	3	3	3	3
2	2	3	3	1	1	1	1	1	1	3	2	2	2	3	3	2	2	2	2	2	3	2	2	3	U	2	3	3	3	3	3	3	3	3
2	2	2	2	2	2	2	2	2	2	3	3	2	3	3	2	1	2	2	3	2	2	3	3	3	U	2	3	3	3	3	3	3	3	3
1	1	1	2	1	1	1	1	1	1	3	2	2	3	3	2	1	3	2	2	2	3	2	2	3	U	2	3	3	3	3	1	3	3	3
1	1	1	2	1	1	1	1	1	1	2	2	2	3	2-3	1	1	3	2	2	2-3	2	2	2	3	U	2	3	3	3	3	1	3	3	3
2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2	2	3	3	3	3	U	2	3	3	3	3	2	3	3	3
2	1-2	3	3	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	NA	3	3	3	3	U	2	3	3	3	3	3	3	3	3
1-2	1-2	3	3	1	1	1	1	1	1	3	3	3	3	2	2	1	1	1	3	NA	2	2	3	3	U	2	3	3	3	3	3	3	3	3
1-2	1-2	3	3	1	1	1	2	2	2	3	3	3	3	2	2	1	NA	NA	3	NA	2	2	3	3	U	2	3	3	3	3	3	3	3	3
2	2	3	3	2	2	2	2	2	2	3	3	3	3	3	3	3	NA	NA	3	NA	3	2	2	3	U	2	3	3	3	3	3	2	2	3
2	2	3	3	2	2	2	2	2	2	2	2	2	3	3	2	2	2	2	3	NA	3	2	2	3	U	2	3	3	3	3	3	3	3	3
1-2	1-2	2	2	1-2	1-2	1-2	2	2	2	2	1	2	3	3	2	2	2	2	2	2	2	2	2	2	U	2-3	2	2	2	3	2	3	2	3
U	U	2	2	U	U	U	U	U	U	2	1	2	3	3	2	2	2	2	2	2	2	2	2	2	U	2	2	2	2	3	2	3	2	3
U	U	2	2	U	U	U	U	U	U	U	U	U	3	3	2	2	2	2	2	2	3	2	2	3	1	3	3	3	3	3	3	3	2	3
U	U	2	2	U	U	U	U	U	U	U	U	U	3	3	2	2	2	2	2	2	3	2	2	3	1	2	3	3	3	3	3	3	2	3
U	U	3	3	2	2	2	2	2	2	3	2	2	3	3	3	3	2	2	2	3	2	2	2	2	U	2	3	3	3	3	3	3	3	3
U	U	3	3	2	2	2	2	2	2	2	3	2	2	3	3	2	2	2	3	1	3	2	3	2	U	2	3	3	3	3	3	3	3	3
U	U	2	2	2	2	2	2	2	2	3	2	2	3	3	3	2	2	2	2	2	3	2	3	3	U	2	3	3	3	3	2	2	3	3

Table 8-1. Fluidic Component Rating Analysis Chart

directed into the interaction region to modify the direction and distribution of the supply flow so that a change in output results at the receiver. Useful amplification occurs, because the change in output energy is usually achieved with a much smaller change in control energy.

Fluid interaction phenomena as presently used in fluidic devices can be divided into three basic categories:

1. Jet Interaction - where the control flow directly modulates the supply flow. The supply jet must be essentially unconstrained by surfaces other than the top and bottom plate in the interaction region.

2. Surface Interaction - where the presence of an adjacent surface is essential to the control action.

3. Vortex Flow - where the existence of a vortex field in the interaction region is essential to the device function.

8.4.2.1 Jet Interaction - In jet interaction devices, control action is achieved through the direct impingement of control flow on the free source (supply) jet. The interaction mechanisms included in this category are beam deflection, impact modulation, and controlled turbulence.

Beam deflection is achieved by installing one or more control ports oriented approximately 90 degrees to the centerline of the supply jet (Figure 8-5). The vector direction of flow from the supply jet is then varied by flow from the control jet. The angular deflection or modulation angle of the supply is essentially a linear function of the control momentum for the small modulation angles normally used in practical fluidic devices. Therefore, for a properly designed receiver, the beam deflection effect can be used to develop a linear proportional amplifier.

Two axially opposed supply jets are used to achieve the impact modulation effect. When the momenta of the two supply jets is equal, a planar impact region is established midway between the two supply jets (Figure 8-6). The shape and location of the impact region can be varied by modifying the momentum of one of the supply jets. This is accomplished by introducing a control flow directly into or transversely across one of the supply jets. This will either increase or decrease the momentum of the jet such that the impact region is displaced axially. When an appropriate receiver is located near the impact region the transverse radial flow from the impact region into the receiver can then be modulated by the control action.

When a laminar supply flow is ejected from a nozzle into a disturbance free medium, the jet flow will remain laminar for a considerable distance downstream from the nozzle and then abruptly become turbulent (Figure 8-7). Controlled turbulence is achieved by introducing a control flow near the exit of the supply jet. This flow disturbs the supply jet causing the point of turbulent breakdown to move axially upstream toward the supply jet nozzle. A receiver or output located between the uncontrolled turbulence point and the controlled turbulence point will sense a significant change in energy level, since the energy recoverable from the source jet is much greater in the laminar region than in the turbulent region.

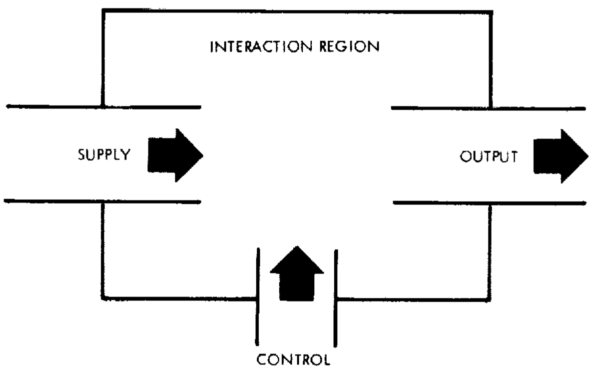


Figure 8-4. Basic Fluidic Device

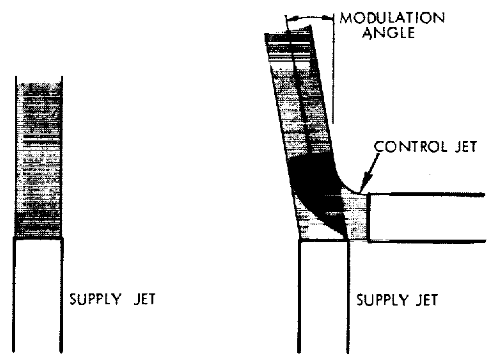


Figure 8-5. Beam Deflection Effect

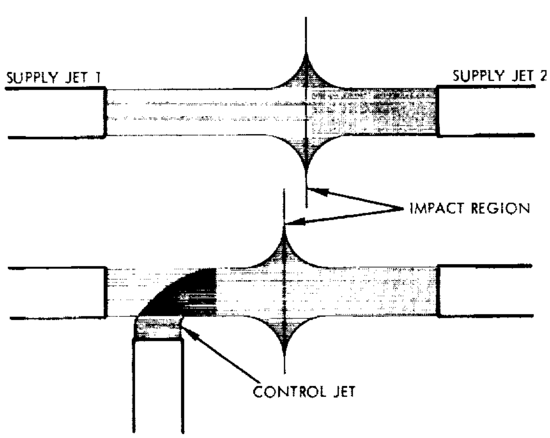


Figure 8-6. Impact Modulation Effect

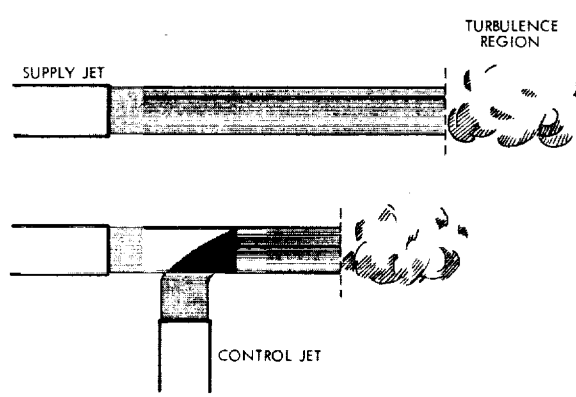


Figure 8-7. Controlled Turbulence Effect

8.4.2.2 Surface Interaction - Some devices depend upon the influence of a nearby or adjacent surface on the supply flow to perform their function. The most important effects are: (a) the attachment of a stream to a surface and (b) separation of flow from a curved surface. In each case, the control function is provided by a control flow although the surface supports and is essential to the device operation.

The mechanism of wall attachment is a primary fluid dynamic phenomena called the Coanda Effect. To understand this effect, consider a supply jet emerging into the area bounded on one side by a wall perpendicular to the jet and on the other side by another wall angled approximately 30 degrees from the supply jet centerline (Figure 8-8). The emerging jet entrains ambient fluid because of high shear at the edge of the jet. On the angled wall side of the jet, the entrained fluid is not easily replaced by ambient fluid so that a transverse static pressure gradient is formed across the jet which bends the jet and forces it to attach to the angled wall. Upon attachment, a low pressure vortex region (or bubble) is formed between the jet and the point of attachment. The vortex is sustained by separated flow near the point of attachment which is returned to the mainstream by entrainment near the supply nozzle. The attached jet may be detached from the angled wall by injecting control flow into the low pressure separation bubble so as to reverse the transverse pressure gradient. The stability of the wall attachment plus the ability to attach and shift the jet make this an extremely useful effect in digital fluidic devices.

The separation effect (Figure 8-9) is based on the tendency of a fluid stream to follow an adjacent gradually curved surface as long as the pressure gradient is larger than the momentum vector. When the radius of curvature of the surface is sharply reduced, momentum will predominate at some point downstream and the flow will separate from the surface. The point of separation can be influenced by injecting control flow upstream of the normal separation point. This reduces the pressure gradient across the jet and thus changes the angle at which the flow leaves the curved surface. Several fluidic devices use this effect to modulate the source flow in one or more receivers located downstream of the controlled separation region.

8.4.2.3 Vortex Flow - To understand this effect, consider a supply flow introduced radially at the centerline of a shallow cylindrical chamber (Figure 8-10). The supply flow enters the vortex chamber and proceeds radially inward with minimal resistance and flows out through the centrally located outlet orifice. The supply port is generally much larger than the outlet orifice so that the outlet flow rate is determined by the area of the exit orifice and system pressures. As control flow is injected tangentially into the chamber, the supply and control flows combine and the resultant flow develops a degree of swirl, dependent on the relative magnitudes of the source and control flow momenta. A forced vortex field is developed within the chamber which varies the pressure gradient across the chamber such that the magnitude as well as the pattern of the source flow is altered. Since the vortex field is essentially a variable resistance, it can substantially reduce or throttle flow and thus provides a unique control function in fluidic devices.

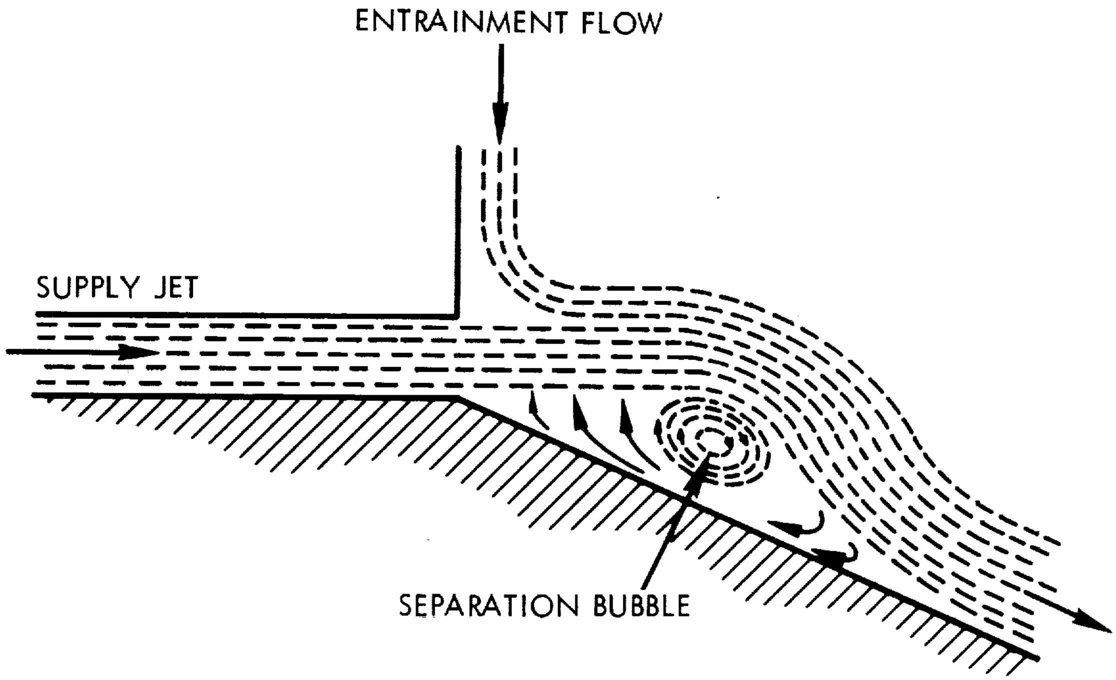


Figure 8-8. The Coanda Effect (Attachment)

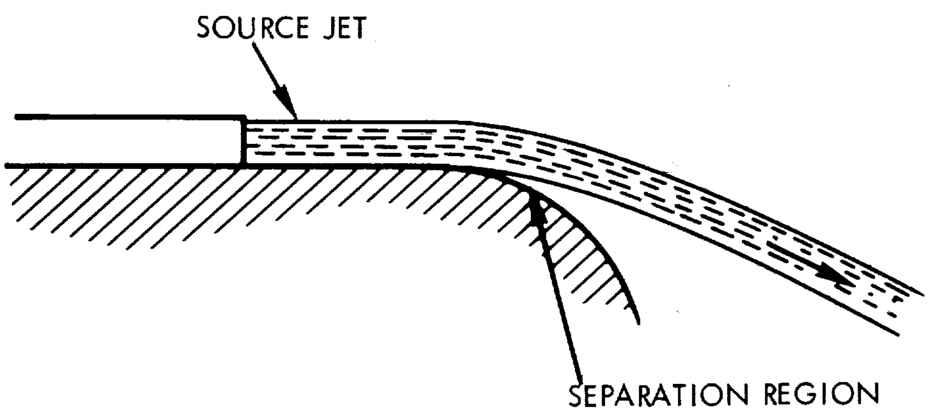


Figure 8-9. Separation Effect

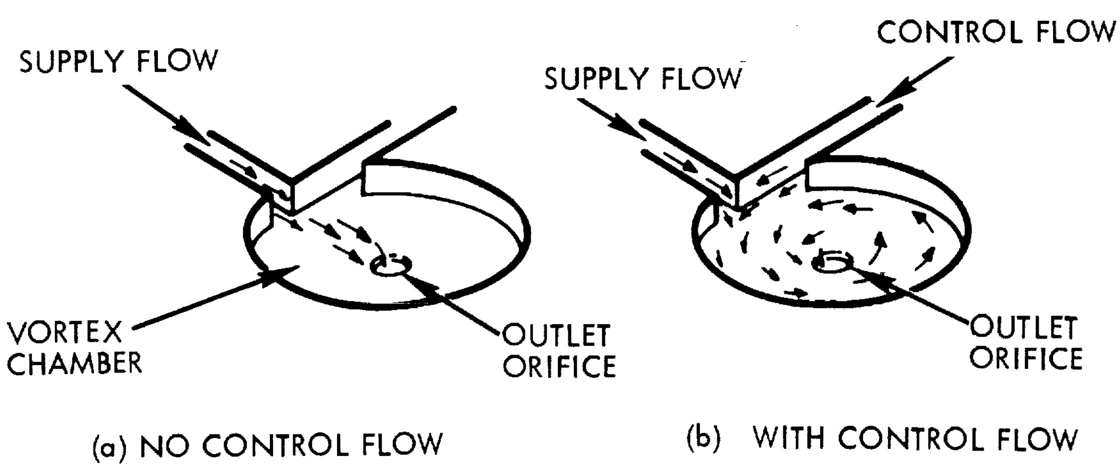


Figure 8-10. Vortex Flow Effects

8.4.3 Wall Attachment Amplifier

The configuration of a basic two-dimensional wall attachment amplifier is shown in Figure 8-11. This device utilizes two walls set back from the supply nozzle, control ports, and channels which define two downstream outputs. Because of the Coanda effect, the device is bistable, i.e., a turbulent free jet emerging from the supply port can be made to stably attach to either wall downstream of the control port. The switching mechanism in the bistable wall attachment device is illustrated in Figure 8-12. Presuming the supply jet is initially attached to the lower wall, fluid is injected through the lower control port into the vortex bubble. When the rate of injected fluid exceeds the rate at which fluid is removed by entrainment, the pressure on the lower edge of the jet will increase. As this pressure becomes greater than the pressure on the upper edge of the jet, the pressure differential is reversed and the jet will detach, cross over to, and attach to the upper wall and remain attached even after the lower control flow is removed.

The operating characteristics of a wall attachment amplifier can be varied by many parameters including pressure, flow, and the physical relationships in the interaction region. The general effects of varying some of the physical parameters, loading, and the power jet pressure are illustrated in Figure 8-13.

A few examples of the many logic elements which utilize wall attachment are shown in Figure 8-14. It should be noted that some of these devices utilize a combination of wall attachment and beam deflection (see Section 8.4.4) to perform logic functions. The digital states of each device can be followed by referring to the accompanying truth table. Operation of the flip-flop or bistable wall attachment device was explained previously. In the OR/NOR gate the interaction region is physically biased so that the supply flow will stably attach only to the adjacent wall leading to output 2. When control flow is introduced at either or both of the control ports, the power stream is shifted to output 1 by beam deflection, and when the controls are removed, the power stream returns to output 2.

The AND gate and half-adder shown in Figure 8-14 are passive elements, i.e., devices that operate on the signal power alone. In the AND gate, control 1 will appear at output 3 only if control 2 is not present, and control 2 will appear at output 1 only if control is is not present. These stable output states are achieved by wall attachment in the respective output ducts. When controls 1 and 2 appear simultaneously (presuming equal control pressures) they combine by beam deflection to produce a signal at output 2. Operation of the half-adder differs from the AND gate in that both controls appear at output 2, control 1 by wall attachment and control 2 by deflection in the opposite cusp. When applied simultaneously, the two controls combine to produce a signal at output 1.

Wall attachment amplifiers provide a fairly high speed of response, average efficiency and relatively high fanout. Versatility and good performance have been demonstrated in a number of applications which are strong recommendations for their continued widespread use. Several fluidic counterparts of the basic electronic and logic elements have been developed, including a

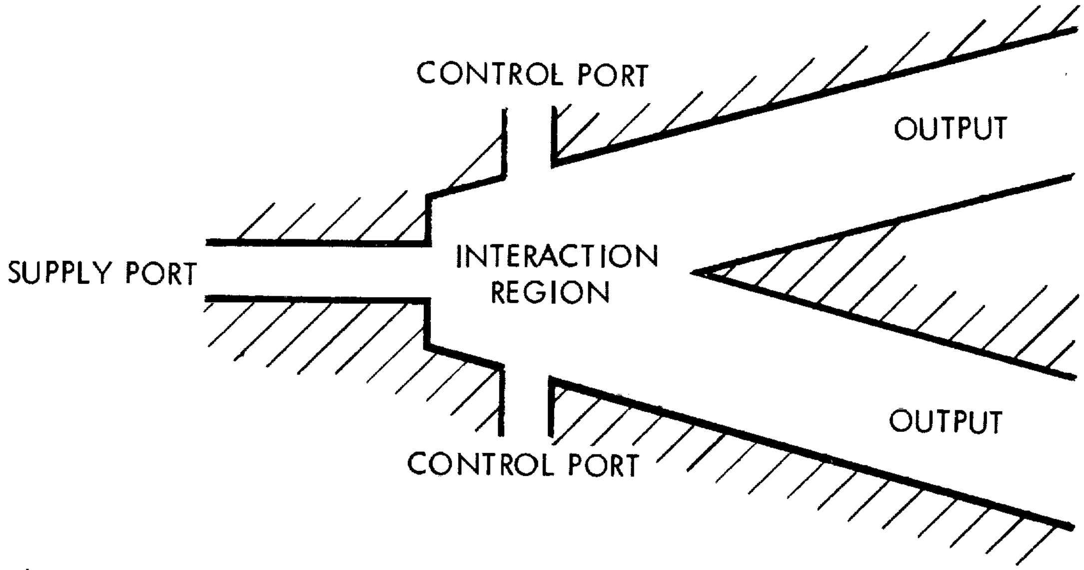


Figure 8-11. Basic Wall Attachment Device

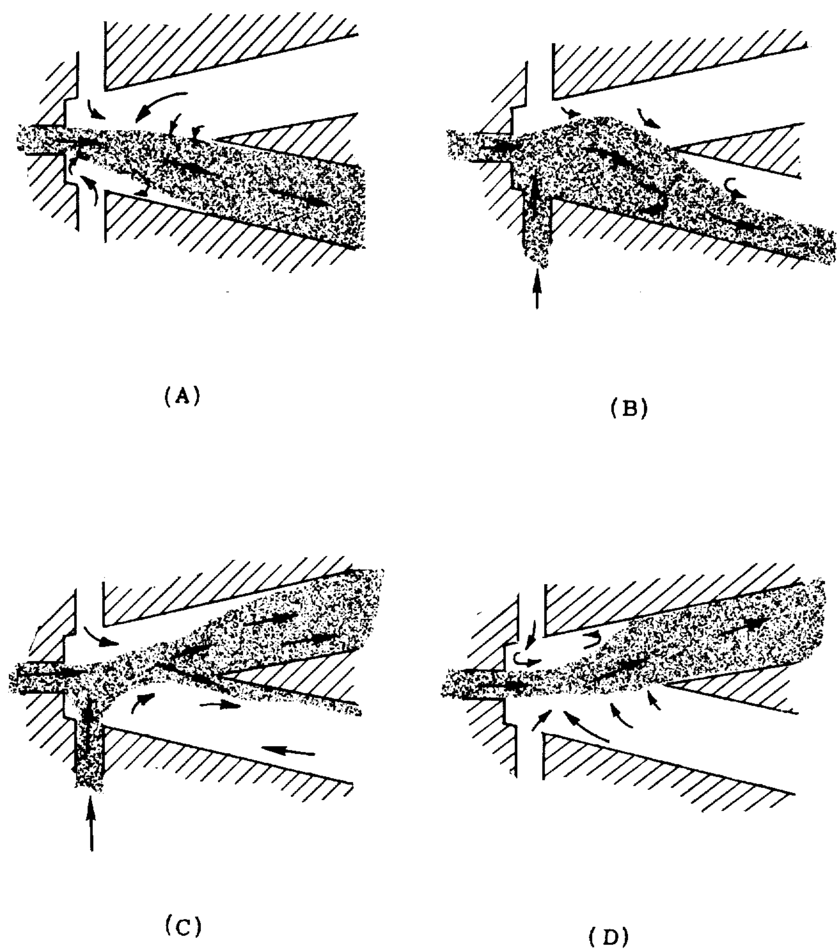


Figure 8-12. Switching Mechanism in Bistable Wall Attachment Device

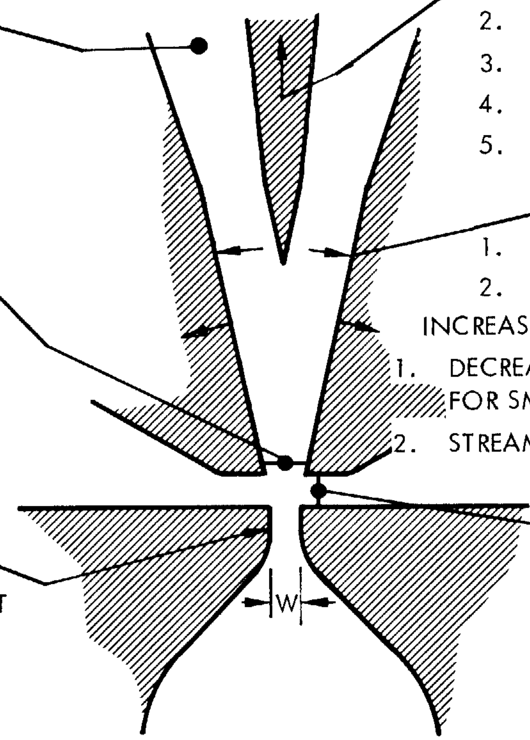
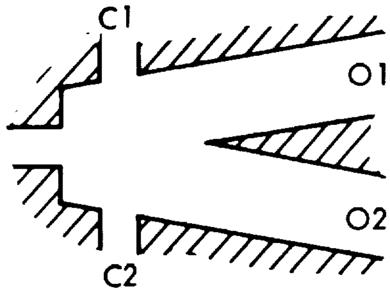


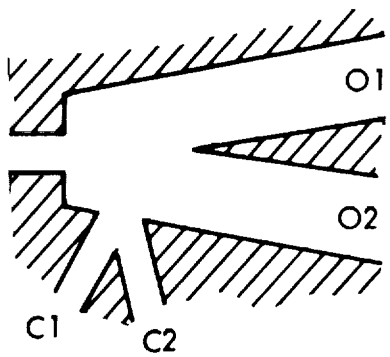
Figure 8-13. Factors Influencing Performance of a Wall Attachment Amplifier

1. FLIP FLOP



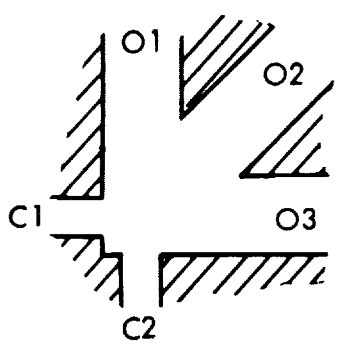
C1	C2	O1	O2
X	O	O	X
O	O	O	X
O	X	X	O
O	O	X	O

2. OR-NOR GATE



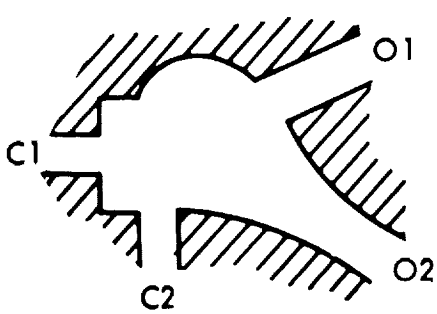
C1	C2	O1	O2
O	O	O	X
X	O	X	O
O	O	O	X
O	X	X	O
O	O	O	X
X	X	X	O

3. AND GATE



C1	C2	O1	O2	O3
X	O	O	O	X
O	X	X	O	O
O	O	O	O	O
X	X	O	X	O

4. HALF ADDER



C1	C2	O1	O2
O	O	O	O
X	O	O	X
O	X	O	X
X	X	X	O

Figure 8-14. Wall Attachment Logic Elements

flip-flop, monostable switch, OR/NOR element, half-adder, and a pulse converter. In considering wall attachment amplifier performance, variation of size in the range from 10 to 25 mils (power nozzle width) or variation of the aspect ratio in the range of 1 to 4 does not appreciably affect performance. Present performance figures are based on air data, however, experimental data indicates that device performance with water or other low viscosity fluid should be similar except that the time response should be considerably slower.

Pressure and flow gains for wall attachment amplifiers typically range from 1 to 15 depending on the fanout. To switch a device, a control pressure of 2 to 15 percent of the supply pressure is normally required. This switching pressure can increase approximately 50 percent with an increase in fanout from 1 to 4. The performance of bistable wall attachment devices is summarized in Table 8-2. Typical performance curves of 3 commercially available wall attachment amplifiers are shown in Figures 8-15, 8-16 and 8-17.

8.4.4 Beam Deflection Amplifier

In the beam deflection amplifier (Figure 8-18), the supply jet emerges into and flows across the interaction region and is divided downstream at the splitter. When there is no control flow or when the control pressures and flows are equal, the supply jet remains axially centered and equal flows issue from each output port. Control flow is directed into the interaction region from nozzles on each side of the supply jet and approximately perpendicular to its centerline. If one control force is made stronger than the other, the supply jet is deflected away from the centerline in the direction of the weaker force and a greater portion of the jet enters the output receiver on that side. In a properly designed amplifier the change in output power is greater than the change in the input control power.

The deflecting force provided by the control streams may be either a pressure or momentum force, both forces are present to some degree in all beam deflection amplifiers. Momentum forces will normally predominate when the controls are set back several supply nozzle widths from the supply jet and pressure forces will predominate when the control nozzle is close to the edge of the supply stream. For proportional operation the static pressure across the supply jet downstream of the interaction region must be zero. To accomplish this, beam deflection devices are specifically designed to prevent wall attachment and the cutouts or side chambers on both sides of the power jet are vented to atmosphere or in some cases to a constant pressure reservoir. The vents also provide overflow ports for the excess fluid in the supply stream and for backflow due to output port loading. Many beam deflection amplifiers also utilize a vent (or centerdump) between the two output ports (Figure 8-19). Although a considerable portion of the supply jet power is lost in this centerdump, it provides several advantages including increased stability with blocked loads and repeatable zero balance conditions (differential output pressure equal to zero) over a wide range of power jet pressure, which is a necessity in high gain staged units.

The beam deflection amplifier is the most widely used of the several types of proportional fluidic amplifiers available. This follows because better technical design information is available in the current literature and several distinct advantages are provided by the two-dimensional planar

Table 8-2. Performance of Bistable Wall Attachment Devices

Parameter	State-of-the-Art		In 5 years
	Typical	Best	
Power Nozzle Size (mil)	5 - 40	10	2 - 10
Aspect Ratio	0.8 - 4	1 - 2	1 - 2
Supply Pressure (psig)	0.1 - 40	1 - 10	0.05 - 5
Switching Pressure* (% of supply)	5 - 15	2	1 - 5
Fan-in	2 - 6	4	8
Fan-out	1 - 16	2 - 4	6 - 8
Nonvented Devices:			
Pressure Recovery @ $Q_o = 0$ (%)	60	85	90 +
Flow Recovery @ $P_o \rightarrow 0$ (%)	70	90	80
Power Recovery (%)	40	50	70
Vented Devices:			
Pressure Recovery @ $Q_o = 0$ (%)	25 - 40	50	75
Flow Recovery @ $P_o \rightarrow 0$ (%)	40 - 70	85	90
Power Recovery (%)	20 - 30	30	40 - 50
Pressure Gain	1 - 15	15	25
Flow Gain	5 - 20	20	30
Response Time (millisecond)	0.1 - 2	0.5 (10 mil nozzle)	0.2 (10 mil nozzle)

* For fan-out of 1, i.e., with the control port of an identical device as a load.

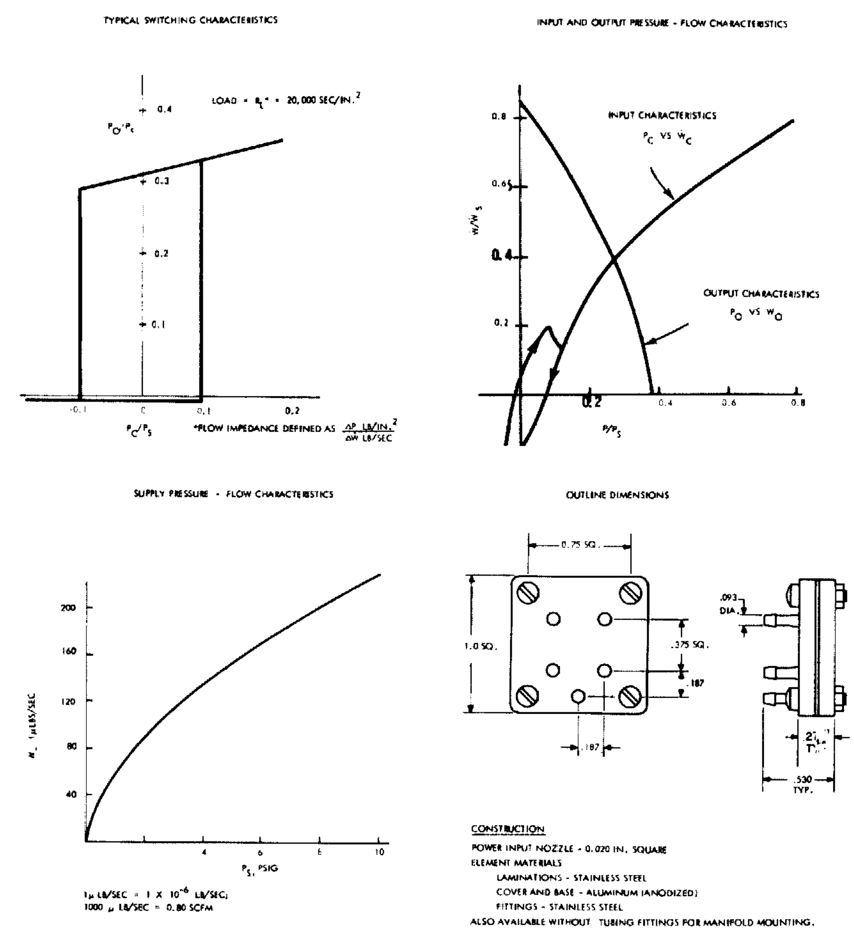


Figure 8-15. Flip-Flop Model DF34 (Courtesy of General Electric)

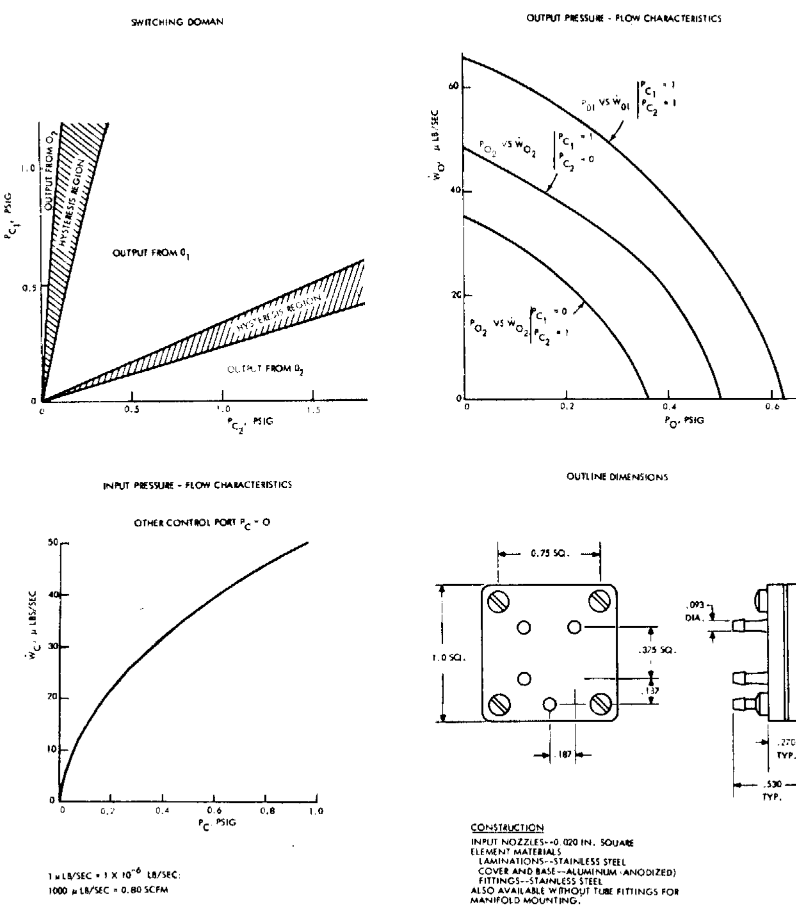


Figure 8-16. OR/NOR Performance (Courtesy) of General Electric)

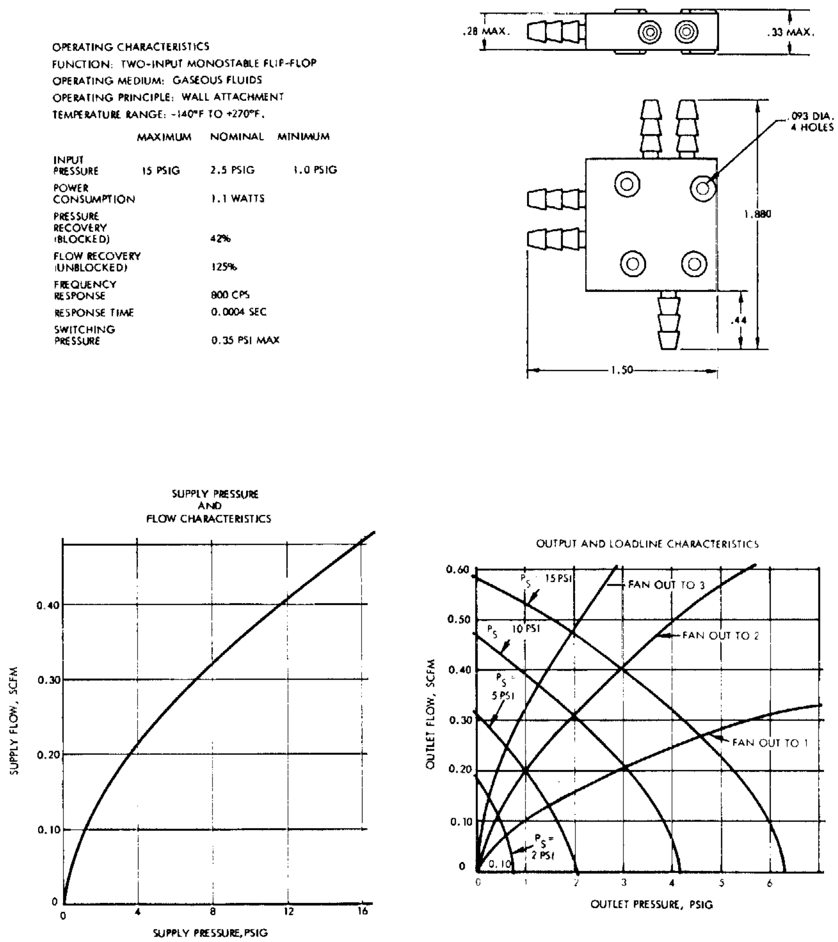


Figure 8-17. Two Input Monostable Digital Amplifier (Courtesy of General Electric)

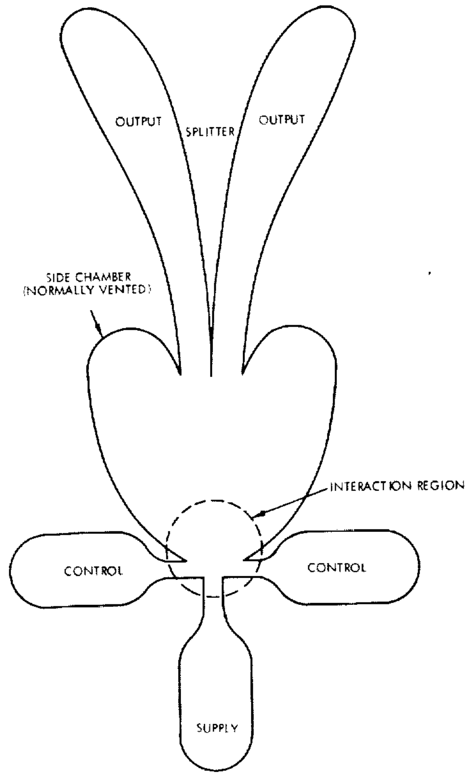


Figure 8-18. Beam Deflection Amplifier Configuration

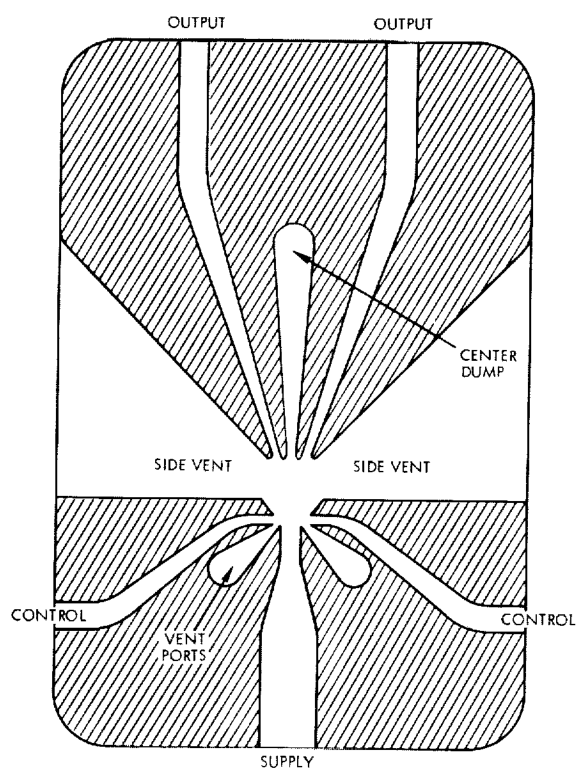


Figure 8-19. Center Dump Proportional Amplifier

configuration. This configuration makes it easier to hold the tight tolerances required, provides the simplest method of cascading amplifiers for high gain and facilitates the development of practical integrated circuits. Beam deflection amplifier size is determined by the width of the power nozzle and the aspect ratio. All of the internal amplifier dimensions are then defined as ratios of the power nozzle width as in wall attachment devices. Normally these devices are made with an aspect ratio of 1 to 2 for best performance.

The single most important criteria in beam deflection amplifiers is the signal to noise ratio. Pressure gain is usually sacrificed in most designs in favor of reduced pressure noise. Signal to noise ratio should be greater than 100 in a high power single stage amplifier and as high as possible in elements suitable for staging; 200 to 400 has been achieved.

The beam deflection amplifier fulfills many critical system functions and is particularly suited to proportional control functions such as sensors, stabilization systems, speed control, temperature control, pressure control, and analog computation. The present state of the art performance of beam deflection amplifiers is summarized in Table 8-3. Typical performance curves of three commercially available amplifiers are shown in Figures 8-20, 8-21, and 8-22.

8.4.5 Vortex Devices

The operation of vortex devices relies upon the amplification mechanism derived by the conservation of angular momentum in a vortex field. This amplification takes place in a shallow two-dimensional vortex chamber as shown in Figure 8-23. As discussed in Section 8.4.2.3, swirl is imparted to a radial supply flow by a tangential control jet which is introduced at the periphery of the vortex chamber. The degree of swirl and the specific method used to generate it depend on the particular vortex device used. As the combined flow proceeds toward the center of the vortex chamber, the tangential velocity of the fluid molecule (Figure 8-23) must increase, since the angular momentum must be conserved. The velocity increase is then inversely proportional to the radial location of the fluid molecule so that if the ratio of the outer to inner radius is very large, the corresponding increase in the tangential velocity will also be great. In practical vortex devices operating on real viscous fluids, the maximum amplification in the flow field is limited by nonlinearities or flow distortions, such as those caused by the degradation of the tangential velocity in the boundary layer at the end walls of the vortex chamber.

8.4.5.1 Vortex Diode - A typical vortex diode (Figure 8-24) has a circular chamber with a tangential inlet and an axial sink at the center of the chamber. Flow through the tangential inlet produces a high pressure loss because of the swirling flow in the vortex chamber. In the reverse direction, flow enters through the axial sink and passes through the vortex chamber without swirl so that the pressure loss is much lower.

The most common performance index for a fluidic diode is the ratio of flow in the easy direction to the flow in the high resistance direction measured at a given upstream pressure. Vortex diodes are presently limited to a flow

Table 8-3. Performance of Beam Deflection Proportional Amplifiers

Parameter	State-of-the-Art		In 5 Years
	Typical	Best	
Power Nozzle Size (mil)	5 - 40	10	5
Aspect Ratio	1 - 3	2	1 - 2
Supply Pressure (psig)	1 - 100	1 - 10	1 - 5
Pressure Gain:			
No Load	2 - 15	20	20 - 25
With Equivalent Load	1 - 10	8	12
With Signal to Noise Ratio > 100	1 - 8	6	10
Flow Gain	10	15 - 20	25
Power Gain	50 - 100	150	200
Pressure Recovery @ $Q_o = 0$ (%)	35	50	70
Flow Recovery @ $P_o \rightarrow 0$ (%)	40	50	60
Power Recovery (%)	20 - 30	30	50
Linearity (%) Of Best Straight Line	2 - 5	1	1 - 2
Linear Range (%) Of Supply Pressure	± 25	± 30	± 50
Maximum Range (%) Of Supply Pressure	± 30	± 40	± 60
Operating Frequency-Gas (kc)	0.1 - 5	1 - 2	2 - 6

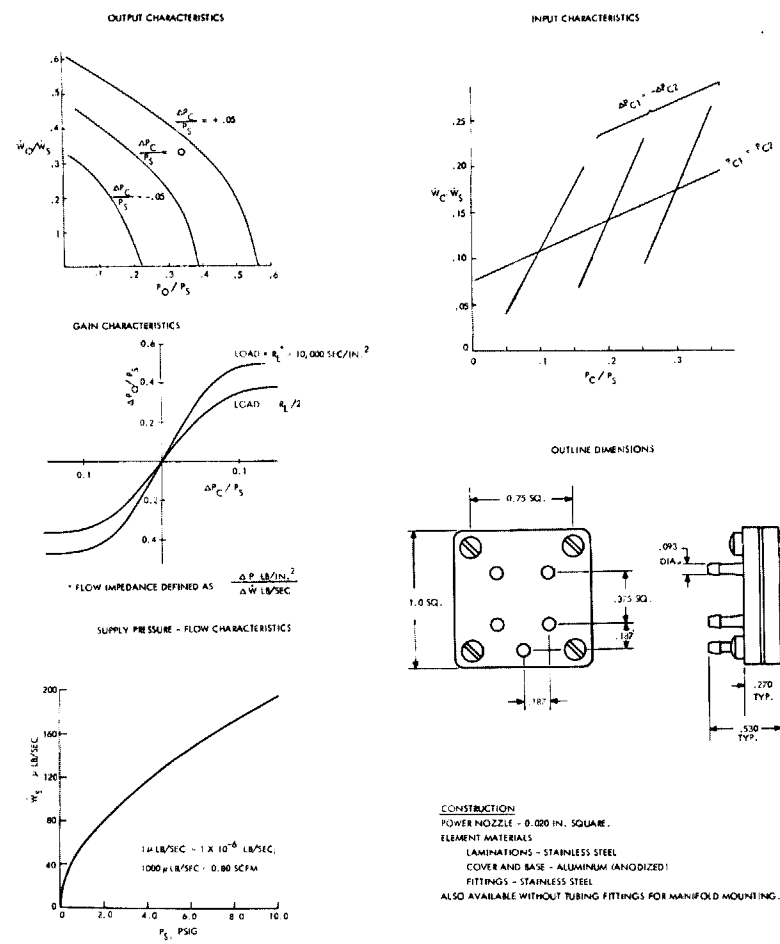


Figure 8-20. Proportional Amplifier Performance (Courtesy of General Electric)

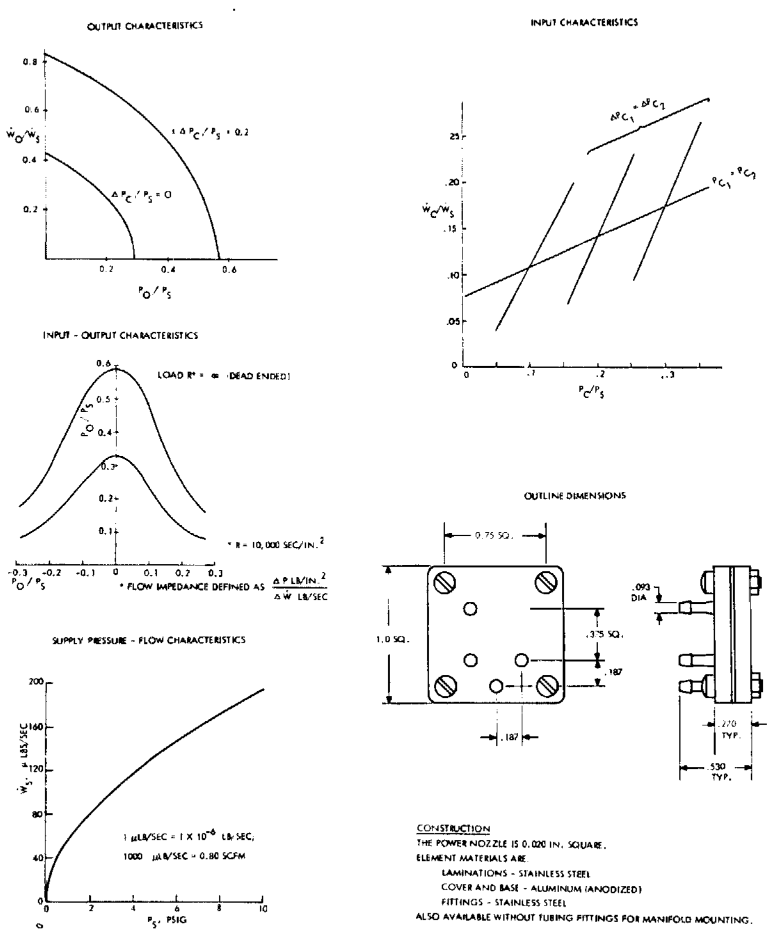


Figure 8-21. Rectifier Performance (Courtesy of General Electric)

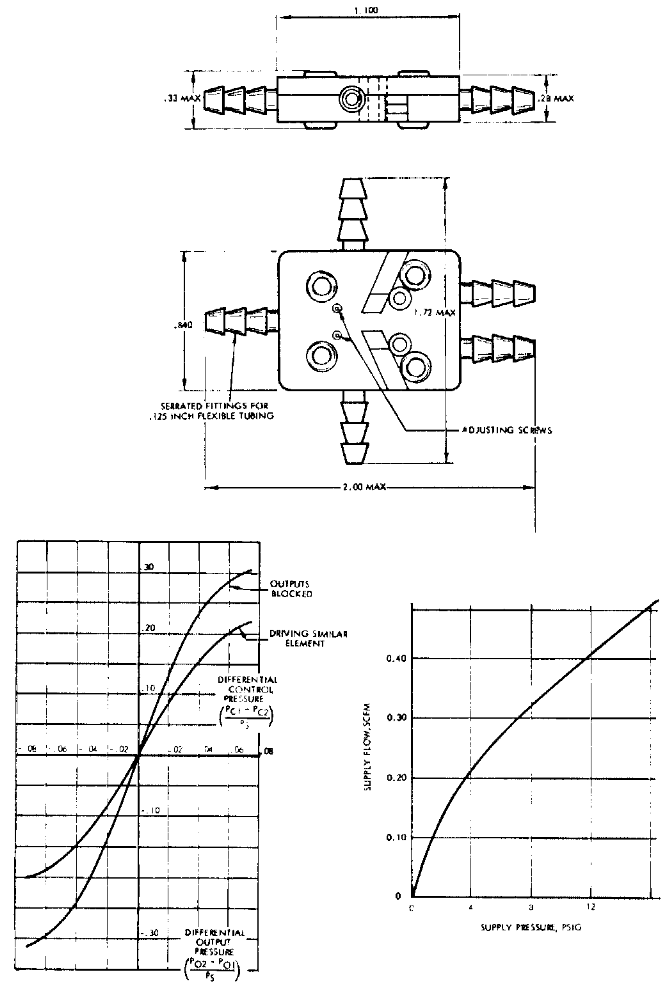


Figure 8-22. Trimable Proportional Amplifier (Courtesy of General Electric)

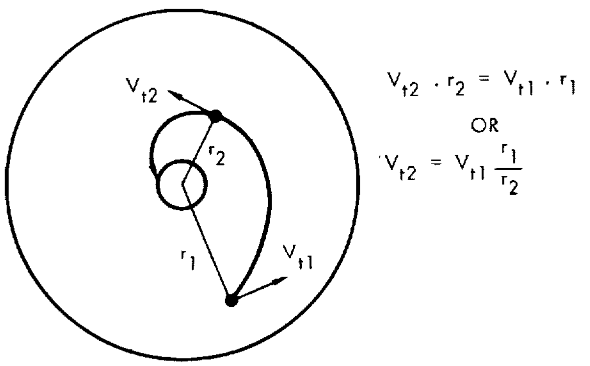


Figure 8-23. Two-Dimensional Vortex Chamber

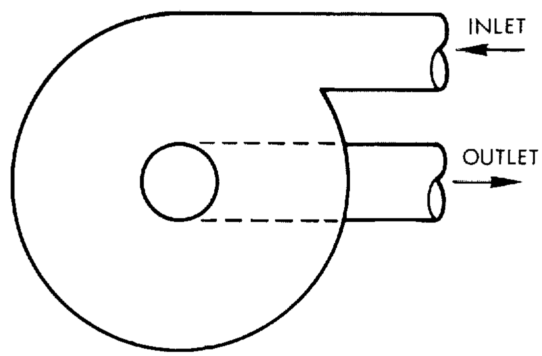


Figure 8-24. Vortex Diode

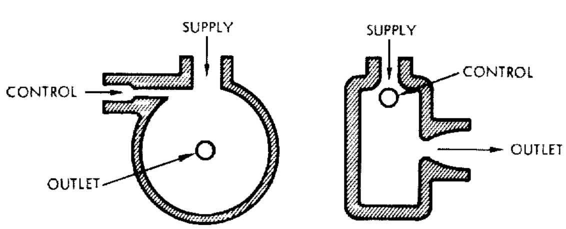


Figure 8-25. Basic Nonvented Vortex Amplifier Configuration

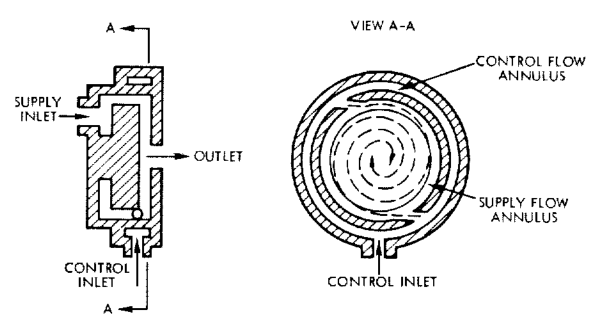


Figure 8-26. Nonvented Vortex Amplifier Button Configuration

ratio of less than 10 and the most common flow ratio is in the range of 3 to 5. A flow ratio of 6.6 (Reference 12) has been achieved by the careful shaping of the tangential inlet port to the vortex chamber. Although the flow ratios achieved in the vortex diode are relatively low, this device has been found useful in many applications.

8.4.5.2 Nonvented Vortex Amplifier - The nonvented vortex amplifier in its simplest form is shown in Figure 8-25. It is similar in construction to the vortex diode except that a third opening has been added for a supply stream, while the original supply port becomes the control port. This configuration is easily constructed in two-dimensional form and although performance is not optimized, it is adequate for many applications.

The performance of the basic nonvented vortex amplifier with a single supply and single control inlet, is not optimum because of the asymmetry of the device. For optimum performance, the supply flow can be introduced into the vortex chamber around the circumference of a button configuration as shown in Figure 8-26. Control flow is then introduced at several points to ensure axisymmetric mixing of the supply and control flows. It is important to note that the control ports must be within the supply flow annulus to prevent the control momentum from being dissipated by a free expansion into the vortex chamber before mixing occurs. This configuration is considered rather complex and consequently, normally made in a three dimensional configuration.

A practical compromise, used by General Electric, is a dual inlet, dual control configuration as shown in Figure 8-27. The two controls and two supplies are connected externally or manifolded together in a cover plate. This device can be easily made in a two-dimensional configuration and its performance is almost as good as the button configuration. A further increase in performance is obtained in the dual exit nonvented vortex amplifier (Reference 19). Dual exits provide an increase in performance of about 70 percent over a single exit vortex amplifier, that is, the maximum flow capacity of the amplifier is increased 70 percent with identical control flows.

A widely used performance criteria for nonvented vortex amplifiers is the turndown ratio. This is defined as the ratio of the maximum and minimum outlet flows at a constant supply pressure. At maximum outlet flow, $\dot{W}_o$, the control pressure, P_c, is generally equal to or less than the supply pressure, P_s, and the supply flow, $\dot{W}_s$, is 0 at minimum outlet flow.

The control to supply pressure ratio at maximum turndown (when $\dot{W}_s$ approaches 0) must also be considered in a nonvented vortex amplifier since the control pressure must always be higher than the supply pressure. This ratio normally varies from about 1.05 to 2, depending on the physical configuration of the amplifier. Nonvented vortex amplifier performance is summarized in Table 8-4, in terms of the turndown ratio at various P_c/P_s in both a single and dual exit configuration. Amplifier chamber diameters were assumed to be one inch or greater since wall effects become a factor below a chamber diameter of one inch and performance will be lower than estimated in the table. The outlet orifice was also presumed to be sonic in the air operated amplifiers although performance will improve somewhat with a subsonic

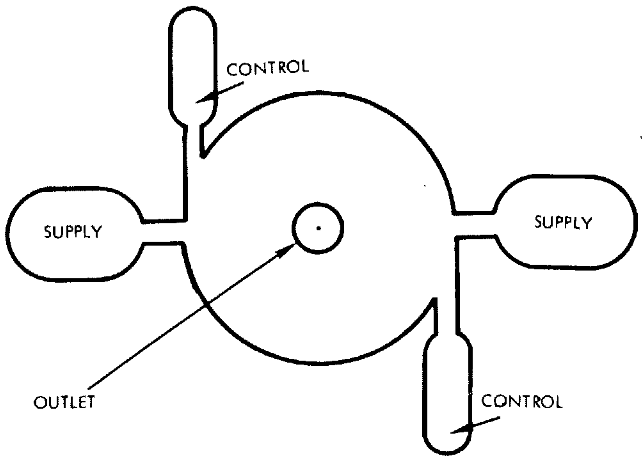


Figure 8-27. Dual Nonvented Vortex Amplifier Configuration

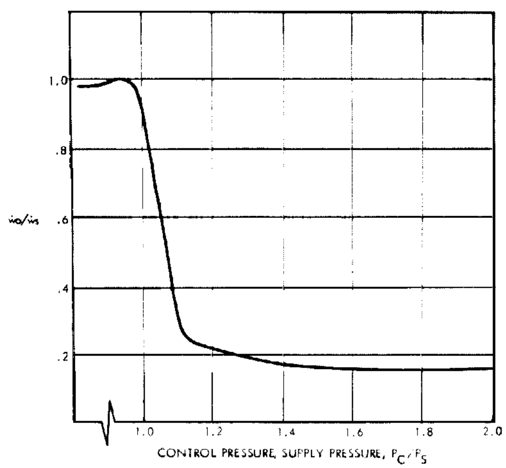


Figure 8-28. Performance of Nonvented Vortex Amplifier (Courtesy of General Electric)

Table 8-4. Nonvented Vortex Amplifier Performance

FLUID	P_c/P_s	TURNDOWN RATIO			
		Single Exit		Double Exit	
		S.O.A.	In 5 Years	S.O.A.	In 5 Years
AIR	1.05	2.5	3.5	U	U
AIR	1.2	5.5	7	8	10
AIR	1.5	8	12	11	16
AIR	2	9	14	U	18
WATER	1.05	U	U	U	U
WATER	1.2	7	9	U	12
WATER	1.5	10	15	U	17
WATER	2	12	18	U	20
HYDRAULIC OIL	1.05	2	4	U	6
HYDRAULIC OIL	1.2	7	9	U	14
HYDRAULIC OIL	1.5	11	15	U	19
HYDRAULIC OIL	2.0	U	20	U	22

S.O.A. - State-of-the-art
U - Information presently unavailable

orifice. Another method of accounting for the control to supply pressure ratio is to plot nonvented amplifier performance as a function of the normalized control pressure (control pressure divided by the supply pressure). The normalized performance curve of a commercially available amplifier illustrates this point (Figure 8-28). The performance curve is generally drawn for a constant supply pressure so that for air operation, when the output port is sonic throughout the operating range, one normalized curve will accurately define performance over a wide range of supply pressures.

The nonvented vortex amplifier can operate with any type of fluid. It has been used with gases, water, hydraulic oils, liquid propellants, and liquid metals. The most efficient operation is obtained with low viscosity fluids such as air and water in that the modulation range is reduced with the higher viscosity fluids. Operational devices have been built in sizes ranging from 0.072 inches to 9 inches in chamber diameter. One type of nonvented vortex amplifier, the vortex throttle, utilizes a gas to control fluids such as water or liquid propellant. Turndown ratios of up to 50 have been reported with the vortex throttle. This device should find wide application in throttling functions where the mixing of small percentages of gas with the controlled liquid is either beneficial or at least not detrimental. For instance, low molecular weight gases have been used to stabilize combustion in several small deep throttling bipropellant rocket engines.

8.4.5.3 Vented Vortex Amplifier - The vented vortex amplifier utilizes a receiver tube which is located and displaced axially away from the vortex chamber outlet orifice as shown in Figure 8-29. With no control flow to the amplifier, the output flow exists from the vortex chamber in the form of a well defined axial jet. Maximum flow is thus recovered in the receiver tube and the recovery characteristic is similar to that achieved in the receiver of a jet pipe valve. When control flow is applied a vortex field is generated within the amplifier and the output flow begins to form into a hollow conical shape such that some of the flow is diverted to the exhaust. With maximum control flow a sufficiently strong vortex is generated so that all of the exiting flow fans out to miss the receiver tube, and the output flow may be modulated fully down to zero.

The vented vortex amplifier is often used as a pressure amplifier as shown in Figure 8-30. Typical pressure gain characteristics for the vented vortex pressure amplifier are shown in Figure 8-31 at several supply pressures and under blocked load conditions. It should be noted that the control pressure must exceed the supply pressure before the characteristic turndown pressure recovery curves are achieved, i.e., no incremental gain is exhibited until the control pressure exceeds the supply pressure. The pressure gain of this particular device is about 10, and gains up to several thousand have been reported for the vented vortex pressure amplifier. These high gains are not useful, however, since they occur only at a single point and under blocked load conditions. The power efficiency for an amplifier which provides useful pressure gain is generally about 50 percent for gases and 65 percent for liquids. Pressure recovery can also be extremely high (95 percent) when operating this amplifier under blocked load conditions with no turndown, although, the flow recovery is zero. A large vented vortex amplifier (output flow of 0.5 lb/sec) has been operated in a power application with flow recovery of about 95 percent and pressure recovery of about 30 percent.

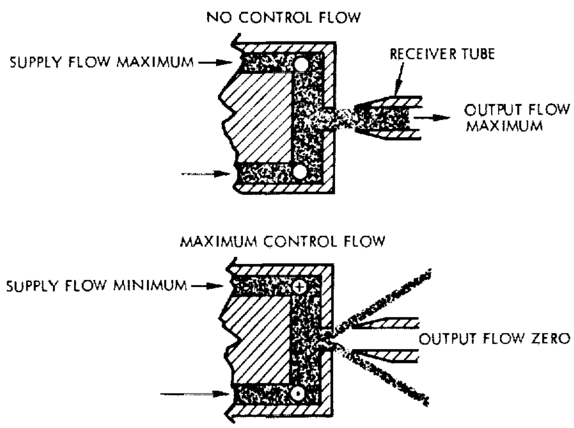


Figure 8-29. Vented Vortex Amplifier

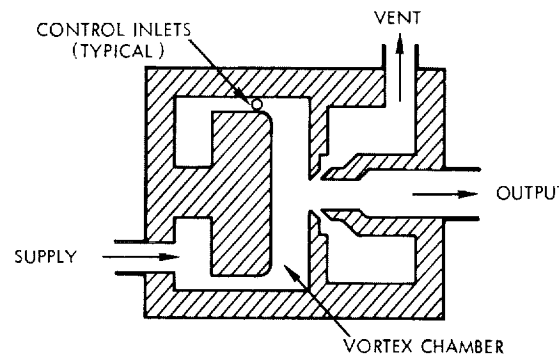


Figure 8-30. Vortex Pressure Amplifier Configuration

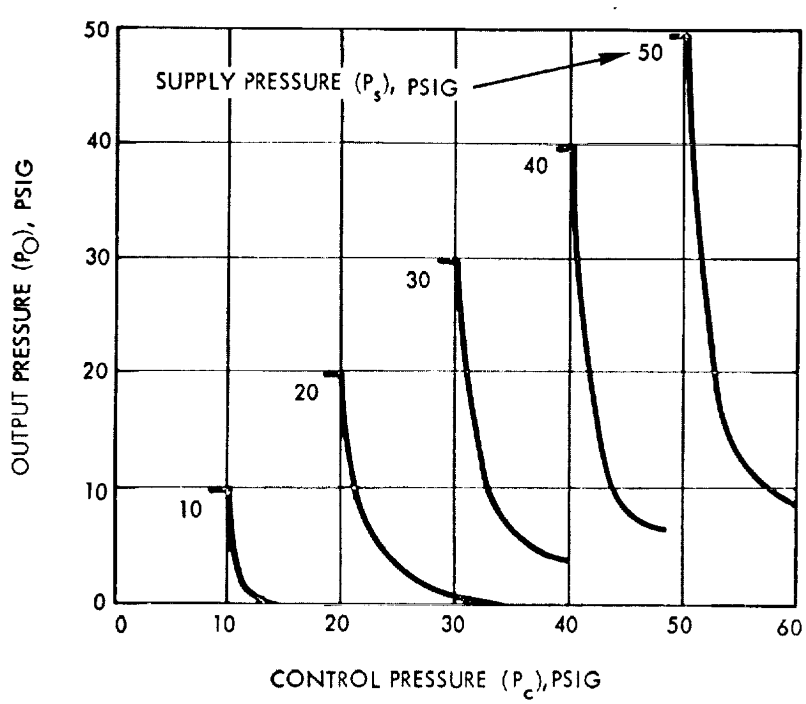


Figure 8-31. Typical Pressure Gain Characteristic Vented Vortex Amplifier

Error detection circuitry is readily implemented with a vented vortex amplifier since there is sufficient room around the outer periphery of the vortex chamber to accommodate a relatively large number of control ports. These ports can be arranged to either aid or oppose each other. For instance, the Bendix Research Laboratories have demonstrated the use of up to 16 separate summing control ports on a one inch amplifier. On the other hand, it is very difficult to sum more than two pairs of control ports in a typical beam deflection amplifier without significant loss in gain and pressure recovery.

8.4.6 Logical NOR Amplifiers

The NOR amplifier has found wide acceptance in the design of relatively low power digital circuits, particularly in industrial applications. In simple terms, the NOR gate provides an output signal when no control signals are present. Since the NOR function is the most basic and universal logic concept, it can be used or interconnected to provide all other logic functions such as AND, OR, NAND, NOT, and flip-flop.

8.4.6.1 Turbulence Amplifier - The turbulence amplifier consists of a supply tube and an output tube precisely aligned in a vented cavity and one or more control input tubes perpendicular to the power jet axis. The supply is introduced into the vented cavity as a laminar stream which is recovered in the output at a relatively high pressure. When one or more control flows are introduced as shown in Figure 8-32, the jet becomes turbulent before reaching the receiver and the output pressure drops sharply.

The controlled turbulence effect (Section 8.4.2.1) is the primary operating principle of the turbulence amplifier, i.e., the transition of flow from the laminar to the turbulent condition. The high gain characteristic exhibited by the turbulence amplifier in the transition region is very useful for digital applications. However, the device is not practical for use as a proportional amplifier because in the transition region the output signal to noise ratio is very low and the output pressure is quite sensitive to small changes in the supply pressure.

Typical static performance characteristics of the turbulence amplifier are shown in Figure 8-33. The curve in the lower left quadrant (1) indicates the supply flow over a range of supply pressures. Output pressure versus supply flow and a family of curves for output pressure versus output flow are plotted in the upper left quadrant (2). Output pressure versus control flow is plotted in the upper right quadrant (3) and control pressure versus control flow in the lower right quadrant (4). Plotting of the curves on a single axis enables fanout to be determined for most any operating pressure. For example, note the minimum control pressure and flow required for turnoff. Then, using the minimum control pressure, check the flow available at that pressure on the proper P_o versus Q_o curve. Maximum fanout is then determined by dividing the Q_o available by the Q_o required. The method is illustrated on the graph by a dotted line.

The turbulence amplifier normally has a fan-in of 4 to 6 and a fan-out of about 6 to 10. Supply pressure range is 0.1 to 1 psig and typical power

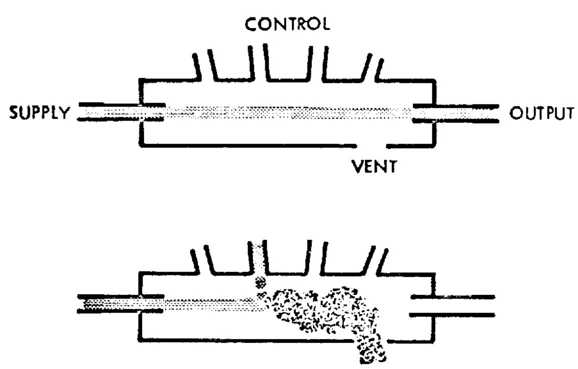


Figure 8-32. Turbulence Amplifier Configuration and Operation

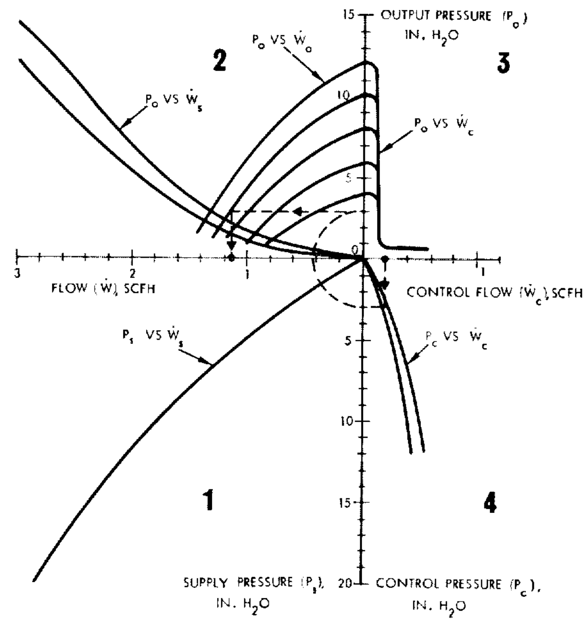


Figure 8-33. Turbulence Amplifier Input-Output Characteristics

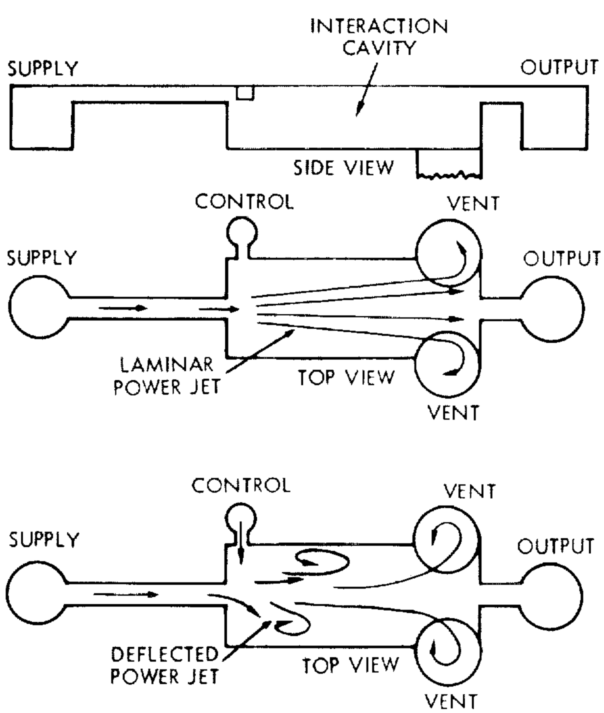


Figure 8-34. Flow Interaction NOR Gate

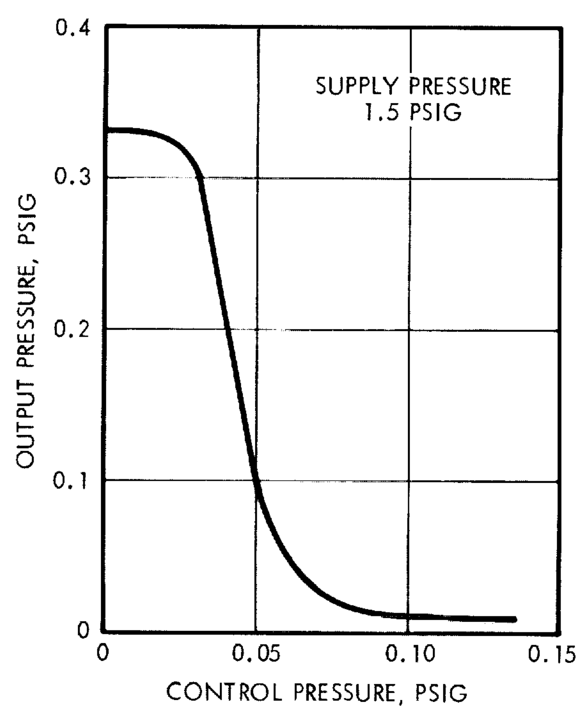


Figure 8-35. Flow Interaction NOR Input-Output Characteristics

consumption is about 60 milliwatts at 0.5 psig. The response time or switching time is in the range of 1 to 2 milliseconds. Turn on time is generally about twice as long as the turn off time because of the relatively long interval required to reestablish laminar flow following the transition to turbulent conditions. The turbulence amplifier also has the advantage of excellent control-output isolation.

The prominent disadvantages of the turbulence amplifier are: (1) sensitivity to sound and vibration in the 5,000 cps range; (2) the requirement for a closely regulated supply; (3) the relatively low supply pressure levels and low output pressure recoveries; (4) low signal to noise ratio.

Application of the turbulence amplifier in aerospace systems does not appear practical because of the disadvantages cited above as well as the inability to integrate the three-dimensional devices and circuits. A planar turbulence amplifier has been developed (Reference 13) which appears practical since it can be assembled in modular circuits. The performance of this planar device is similar to that of the three-dimensional turbulence amplifier except that improved output pressure recovery and decreased sensitivity to sound and vibration is claimed.

8.4.6.2 Flow Interaction NOR Amplifier - The flow interaction NOR amplifier (Figure 8-34) operates somewhat like the turbulence amplifier. Laminar flow is developed in the long supply nozzle and the power jet remains laminar as it flows through the interaction cavity and reaches the output receiver. The power jet flows adjacent to the top plate as it moves through the interaction cavity and the presence of the top wall reduces the effects of ambient noise. Control flow deflects the power jet to the side and away from the top plate to reduce the output pressure. A portion of the deflected supply jet also tends to recirculate in the interaction cavity and acts as a positive feedback which further disrupts the jet and decreases the output even further.

This NOR amplifier has a supply pressure range of 1 to 1.6 psig, a power consumption of about 23 milliwatts at 1.5 psig, and a fan-in and fan-out capability of 4. The response or switching time will vary from 1.5 to 3 milliseconds as the fan-out is increased from 1 to 4. A typical input/output characteristic for a supply pressure of 1.5 psig is shown in Figure 8-35.

Commercially available flow interaction NOR amplifiers are fabricated in 22 amplifier modules. Although this amplifier is adaptable to integrated circuits, it suffers from the same disadvantages cited for the turbulence amplifier, in particular, low output pressure level, low signal to noise ratio, and the need for a well regulated supply.

8.4.6.3 Two-Dimensional Laminar NOR Amplifier - The operation of the laminar NOR amplifier (Figure 8-36) depends on the deflection of a laminar supply jet rather than the laminar turbulence transition which is characteristic of the turbulence amplifier. In this device, the adjacent side wall and the top and bottom walls are a strong stabilizing influence on the supply jet as it flows to the output port. When a control signal is applied, the supply flow is deflected into the vent port. The additional vent holes in the

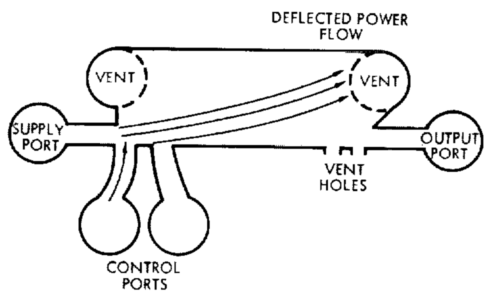


Figure 8-36. Laminar NOR Gate

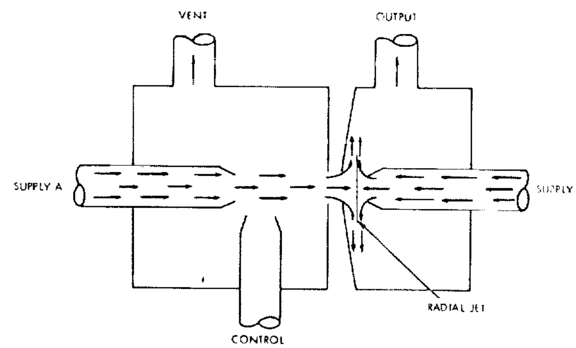


Figure 8-37. Impact Modulator NOR Gate

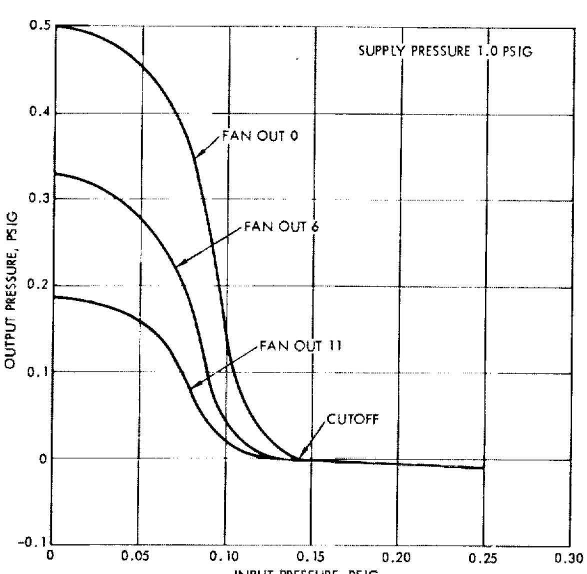


Figure 8-38. Impact Modulator NOR Input-Output Characteristic

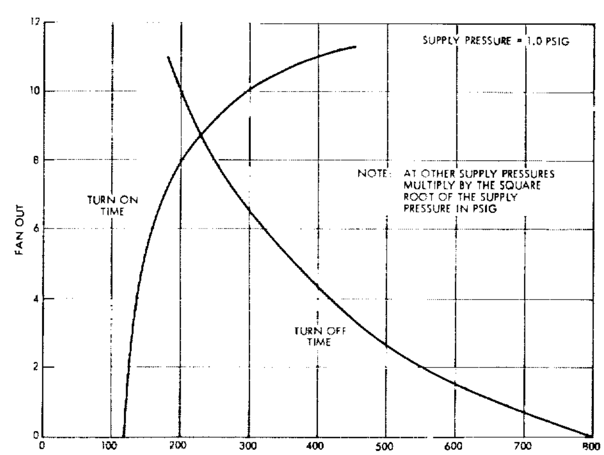


Figure 8-39. Impact Modulator NOR Switching Time

straight wall immediately upstream of the output port are required to decrease the static pressure buildup along the wall when the output port is blocked. The vents provide improved blocked output performance as well as a significant increase in the blocked output pressure recovery.

The laminar NOR amplifier uses a .020 x .020 inch power nozzle and consumes about 2 milliwatts of fluid power at a supply pressure of 0.1 psig. Response time measurements have not been made as yet, but response is estimated to be about 10 milliseconds which is relatively slow compared to other logical NOR units. Performance curves are not presently available, but the output pressure recovery is estimated to be about 50 percent of the supply and experimental units have shown a fan-out capability of 2 and a maximum fan-in capability of 2.

It is anticipated that these excellent low power elements will be adapted to miniaturized integrated circuits and should find widespread application in aerospace systems. One obvious application is in start-run-shutdown sequencing and other similar digital circuits. Reliability estimates should be high because of the relatively large power nozzle. The switching time is certainly more than adequate for most applications and usually will be outweighed by the compactness and low power consumption of the amplifier.

8.4.6.4 Impact Modulator NOR Amplifier - In the impact modulator NOR gate, (Figure 8-37) two submerged jets emerge from opposed supply nozzles along the same axis so that they impact and form a radial jet. The axial location of this radial jet depends upon the momentum of each of the two impinging jets. A concentric orifice is placed between the two supply nozzles such that the radial jet is enclosed in an output chamber and separated from a vented chamber. Transverse control jets are applied to the supply jet in the vented chamber, this reduces the axial momentum of this jet so that the radial jet moves into the vented chamber and the output pressure is drastically reduced.

This NOR gate is particularly well suited to logic applications because of its high input and output impedances and a high pressure gain. There is also complete isolation between individual control inputs as the control signals are applied in a completely vented chamber. Any changes in output conditions do not affect input pressure and flow because of the concentric orifice separating the output and the vented chambers.

The impact modulator NOR gate has a fan-in of 4 and a fan-out of 11. Supply pressure range is 0.25 to 6 psig and power consumption is 0.2 watts at 1 psig. Typical control-output pressure characteristics at 1 psig supply pressure and switching times are shown in Figures 8-38 and 8-39. The response or switching time averages about 300 microseconds at a supply pressure of 1 psig, which is good when compared to other fluidic logic elements of similar power drain. It should be noted, however, that the switching time varies drastically as a function of fan-out and turn-off time is several times longer than the turn-on time.

The relatively complex three-dimensional configuration of the impact modulator NOR will limit its application in aerospace systems. Injection molding appears to be the only logical manufacturing technique at the present time and this limits the device to relatively low temperature operation.

Current gates are approximately 3/4 inch in diameter 1-1/4 inches long and not adaptable to integrated circuit blocks.

8.4.6.5 Focused Jet Amplifier - The focused jet amplifier (Figure 8-40) utilizes an inwardly directed annular jet which adheres to the upper surface of a flow separator by wall attachment so as to form a focused jet which is collected at the output tube. The application of an annular control signal prevents attachment of the power jet to the flow separator and the flow is directed away from the output tube so that the output flow is greatly reduced.

The output pressure range of the focused jet is 3 to 14 psig and switching speeds range from 0.3 to 0.6 milliseconds. The switching of the jet is not completely snap action but the device is not suited for proportional operation. Typical fan-in is 4 and fan-out is 6.

The power consumption of the focused jet is relatively high because of the large axisymmetric aspect ratio. The high power requirement with no significant performance gains will limit the application of this device. The axisymmetric configuration is also considerably more expensive to manufacture than a two-dimensional NOR gate.

8.4.7 Special Devices

8.4.7.1 Boundary Layer Amplifier - The boundary layer amplifier (Figure 8-41) relies upon the forced separation of a stream flowing over a curved surface for its operation. With no control flow, the supply flow adheres to the adjacent curved surface until well downstream of the control duct so that the supply flow misses the output and is vented. As control flow is applied into the boundary layer of the curved surface, the point of separation moves upstream so that the supply flow is directed into the output duct.

A typical boundary layer amplifier in a two-dimensional configuration is shown in Figure 8-42. Bias flow is used in this device to force the power jet to unlock and return to the off position when the control flow is removed. The number and location of the control slots have a significant effect on the characteristics of the amplifier, and the island functions to eliminate output hysteresis effects.

The boundary layer amplifier is used primarily when a high input impedance power amplifier is required. Typical pressure gains are 2 to 3, flow gains 20 to 30, and power gains 60 to 80 which hold at relatively low supply pressures (about 5 psig). This device is limited by its low power gain, relatively complex construction, and slow response time.

8.4.7.2 Double Leg Elbow Amplifier - The elbow amplifier (Figure 8-43) is essentially a more complex version of the boundary layer amplifier. The primary differences are that it has a passive input channel and two output ducts. Without control flow the momentum flux in the active input channel is low near the outlet of the passive inlet channel so that the combined flow is directed into the left output channel. As control flow is applied, the point at which flow in the active leg separates from the channel wall moves upstream as in the boundary layer amplifier. As this occurs, the momentum distribution across the flow changes such that the combined flow

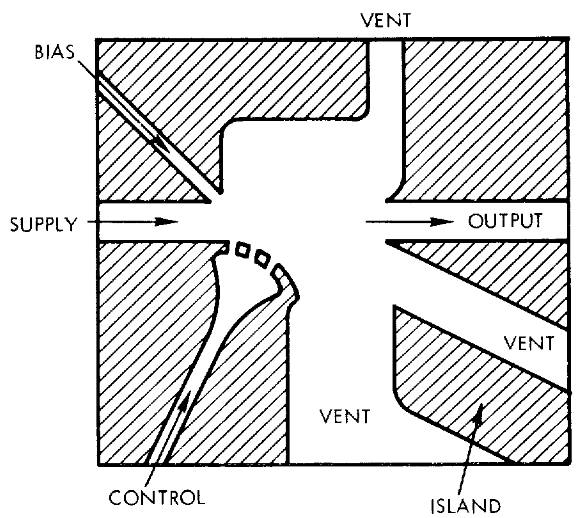


Figure 8-40. Focused Jet Amplifier

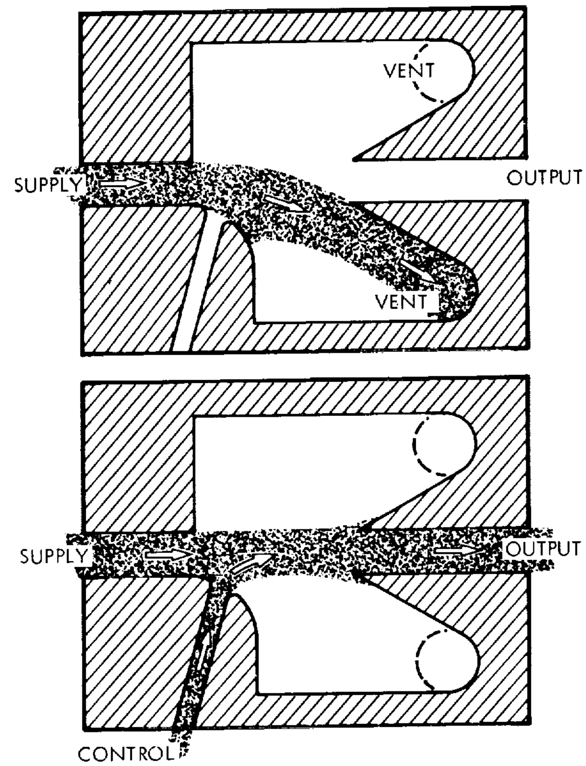


Figure 8-41. Boundary Layer Amplifier Operation

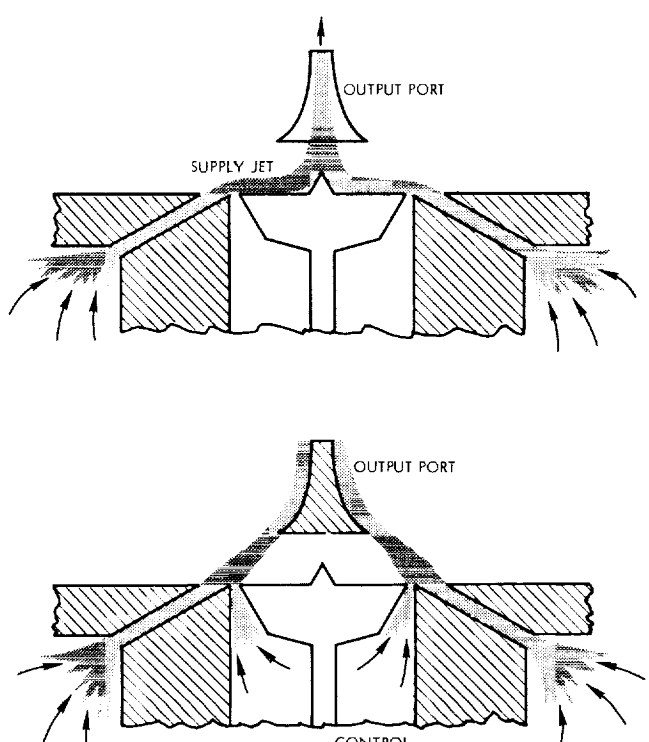


Figure 8-42. Boundary Layer Amplifier Configuration

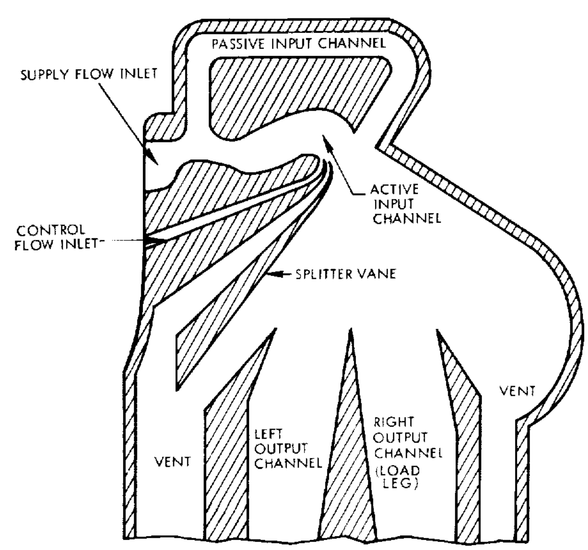


Figure 8-43. Double Leg Elbow Amplifier

moves toward the right output channel. The control action is proportional since the portion of the power stream which flows into either of the output ports depends upon the momentum distribution of the combined active and passive flows.

This amplifier provides exceptionally high flow gain, however it is limited to low pressures and low operating frequencies. Typical flow gain is 200 with a corresponding power gain of about 40. The maximum demonstrated gains under static conditions are flow gain 300, pressure gain 3, and power gain 500. Performance of this amplifier drops drastically as the operating frequency is increased. Typically, the performance is down 3 db at 10 cps and 10 db at 40 cps.

8.4.7.3 Induction Amplifier - The induction amplifier (Figure 8-44) is essentially a back to back arrangement of two airfoils. As the power jet is turned on the flow will adhere (by asymmetry or through the use of a bias pressure) to one of the airfoil shaped boundaries downstream of the power nozzle. Presuming that the flow is originally coming out of the left output duct, a control signal must be applied to the right control duct to switch the flow. The control stream from the right control duct adheres to the outside wall of the right output duct. This flow functions to reverse the transverse pressure gradient across the power jet and thus cause the power jet flow to switch to the right output duct.

Except for the switching principle, the characteristics of this device are similar to those of the wall attachment amplifier.

8.4.7.4 Edgetone Amplifier - The edgetone amplifier (Figure 8-45) is a high speed flip-flop which utilizes a fluid dynamic phenomena called the edgetone effect. Consider a fluid jet impinging on the tip of a wedge such as the tip of the splitter shown in Figure 8-45. With the proper amplifier configuation, the supply jet will continuously oscillate back and forth across the wedge tip alternately shedding vortices on each side. An output occurs in the edgetone amplifier when the power jet stably oscillates between the tip of the wedge shaped splitter and the cusp at the entrance to the output duct in use. The controls are utilized to switch the power stream to the opposite output duct where stable oscillation is again established.

The primary functional differences in the edgetone amplifier from a typical wall attachment amplifier are the faster switching time (0.1 millisecond or less) and the lower control pressures required.

8.4.7.5 Impact Modulators - Impact modulation is a jet interaction phenomena that is achieved by the use of two axially opposed power jets which provide a planar impact region (see Section 8.4.2.1). There are two versions of this device, the transverse impact modulator and the direct impact modulator.

In the transverse impact modulator (Figure 8-46) maximum output is obtained when the planar impact region is closest to the output duct. When a transverse control signal is applied, the momentum of the left supply jet is decreased and the impact region moves to the left. The device functions as a proportional amplifier with negative gain since the output flow and pressure decrease as the control pressure and flow are increased.

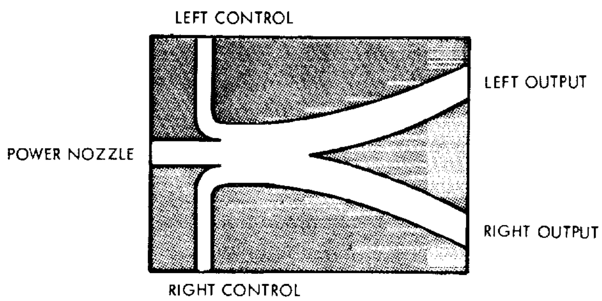


Figure 8-44. Induction Amplifier

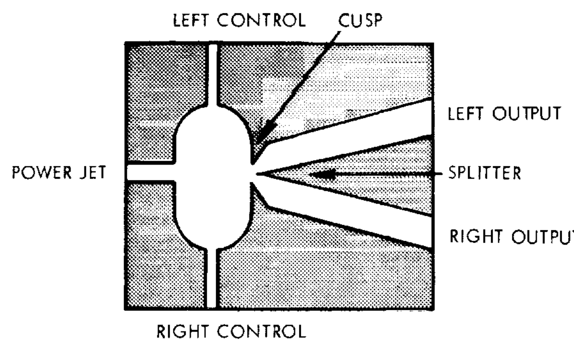


Figure 8-45. Edgetone Amplifier

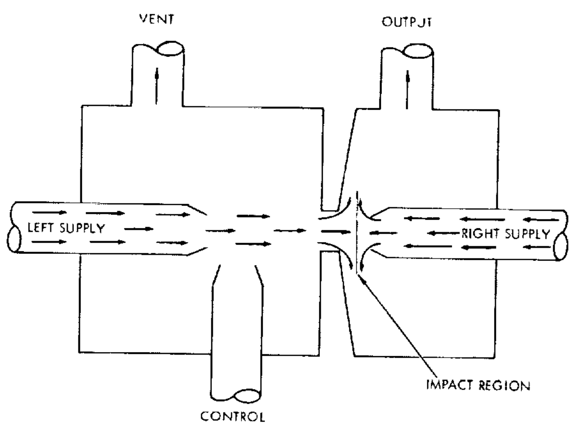


Figure 8-46. Transverse Impact Modulator

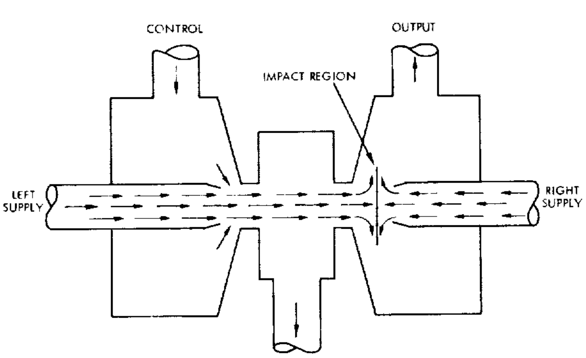


Figure 8-48. Direct Impact Modulator

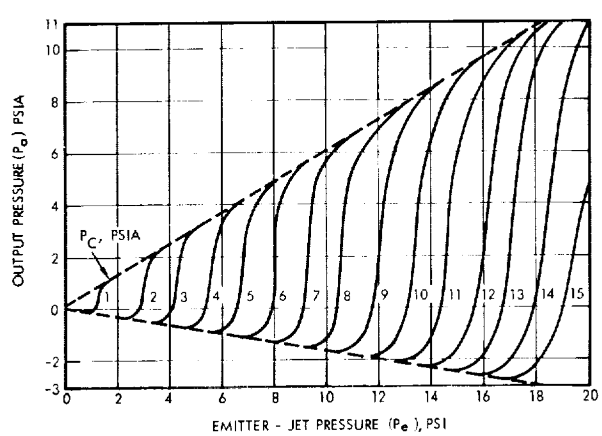


Figure 8-47. Transverse Impact Modulator Performance

A performance curve of a typical transverse impact modulator is shown in Figure 8-47. The flow gain varies from 5 to 30 and the no-load pressure gain is between 20 and 40. Four element cascades have given pressure gains of about 12,000 which reduces the average pressure gain per stage to about 10.5. This is necessary to ensure output linearity and proper interstage impedance matching.

In the direct impact modulator (Figure 8-48) the supply flows and pressures are adjusted so that the planar impact region is closer to the left supply jet. As the concentric control signal is applied, the momentum of the left supply jet is increased and the impact region moves to the right. This results in increased output flow and pressure as the control flow and pressure are increased so that the device is a proportional amplifier with positive gain.

Pressure gains up to 200 have been reported for the direct impact modulator which is a significant improvement over the transverse impact modulator. The input impedance is also variable and can be adjusted to approach infinity.

Impact modulators are attractive for proportional control application because of the high pressure gain per stage and the high control input impedances. Unloaded frequency response is reportedly quite high (300 to 400 cps), however, this has not been related to a particular element size and response will decrease markedly when the element is loaded. Signal to noise ratio ranges from 60 to 300. The difficulty in obtaining reproducible characteristics from one device to another is one of the major obstacles to the development of impact modulators. The three dimensional concentric nozzle configuration is also quite expensive to manufacture except by injection molding.

8.4.8 Oscillators

Fluidic oscillators require feedback for operation just like their electronic counterparts. There are several types, which have been utilized in timer circuits, temperature sensors, pressure references, and in analog to digital converters.

8.4.8.1 Wall Attachment Oscillators - An external feedback oscillator which utilizes a wall attachment flip-flop and two output feedback loops is shown in Figure 8-49. When the supply flow is initially turned on, the power jet will attach to either the left or right wall and flow out the respective output duct as in a normal flip-flop. Presuming the power jet is initially attached to the right wall, part of the power stream is returned to the right control by the external feedback loop so that the power jet is switched to the left wall when the right control pressure reaches the correct switching pressure. This process repeats itself on each side so that the power jet oscillates at a frequency which depends on the sum of the transit time of the fluidic signal through the feedback path and the power jet switching time.

The coupled control oscillator also utilizes a fluidic flip-flop and a feedback loop joining the two control ports (Figure 8-50). Assuming that the power jet is about to attach to the right wall, a rarefaction wave due to the suddenly increased entrainment at the right control port travels around

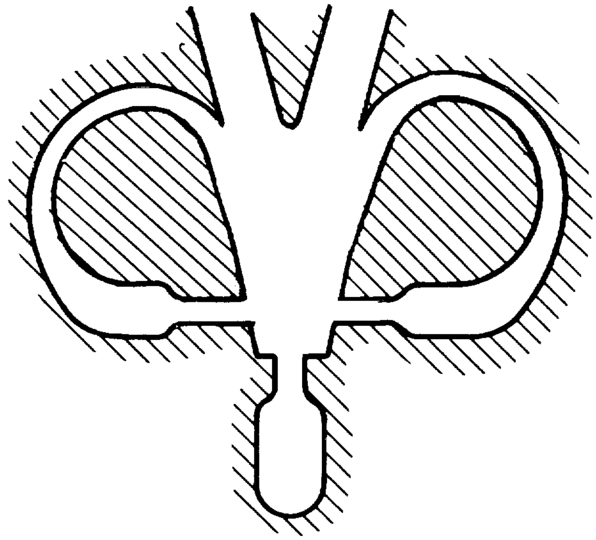


Figure 8-49. External Feedback Oscillator

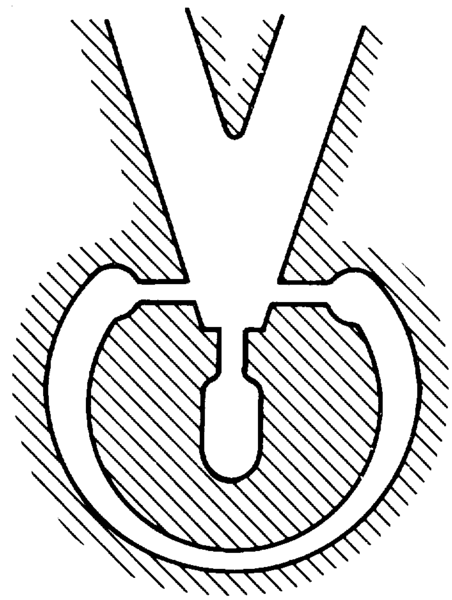


Figure 8-50. Coupled Control Oscillator

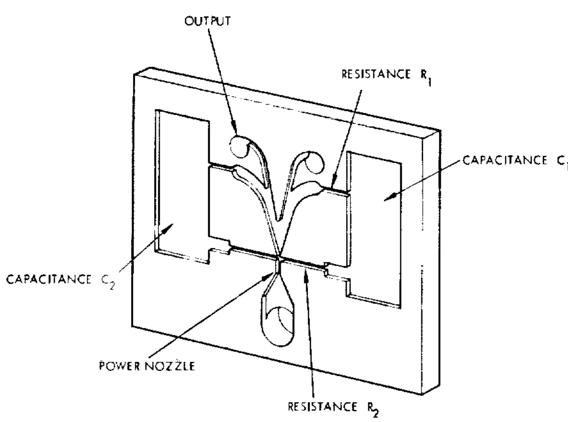


Figure 8-51. Relaxation Oscillator

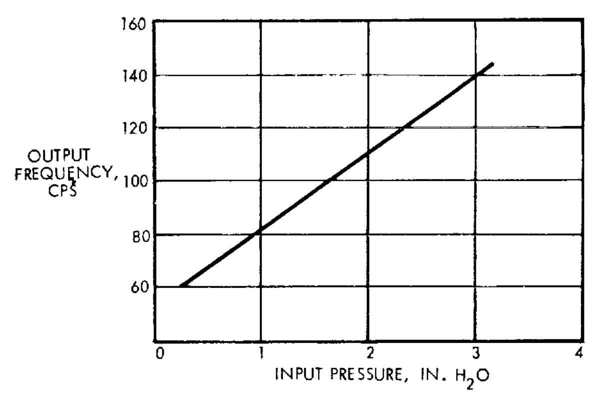


Figure 8-52. Pressure Controlled Oscillator Performance

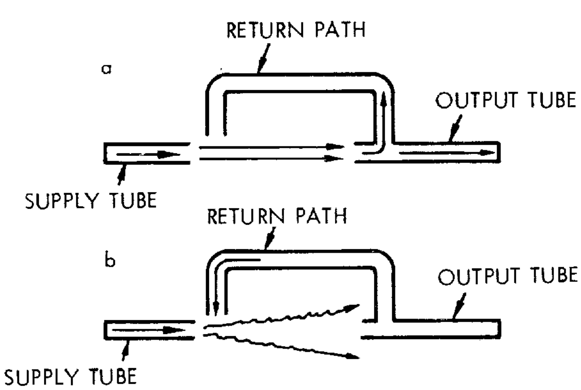


Figure 8-53. Turbulence Amplifier Oscillator

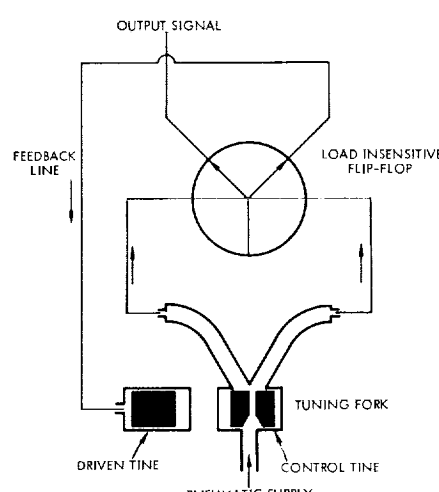


Figure 8-54. Fluidic Tuning Fork Oscillator

the control passage and is reflected at the left control port. This reflected wave, a compression, then travels back to the right control port causing the jet to switch to the left wall and the process is repeated.

8.4.8.2 Relaxation Oscillator - This oscillator is essentially an external feedback oscillator with a lumped RCR (resistance-capacitance-resistance) network in each of the output feedback loops (Figure 8-51). The RCR network makes the relaxation oscillator relatively insensitive to temperature and pressure. However, careful design is necessary if pressure and temperature insensitivity are required together.

The relaxation oscillator was developed by the Harry Diamond Laboratories for use in pneumatic timers and logic circuits that must operate under severe environmental conditions (Reference 14). A prototype oscillator has demonstrated less than $\pm$ 2% frequency change over a supply pressure range of 6 to 30 psig. A frequency variation of less than 1% was also obtained over a temperature range from 77 to 175°F at a constant pressure.

8.4.8.3 Pressure Controlled Oscillator - This oscillator is another special form of the external feedback oscillator (Figure 8-49), which varies in output frequency as an approximately linear function of the supply pressure. This is accomplished by varying the RLC (resistance-inductance-capacitance) components in the output feedback loops. The pressure controlled oscillator can use either a wall attachment flip-flop or a jet interaction proportional amplifier to achieve the gain necessary for oscillation.

The pressure controlled oscillator (PCO) is used for analog to digital conversion in fluidic frequency modulated systems and as a pressure reference. One experimental PCO operates with a gain of 30 cps per inch of water (800 cps per psi) as shown in Figure 8-52. This particular oscillator only has a useful range of about 80 cps but an important advantage is that it can operate at very low pressures with excellent resolution.

8.4.8.4 Turbulence Amplifier Oscillator - This oscillator (Figure 8-53) utilizes a turbulence amplifier and a single output feedback loop as used in the external feedback oscillator. When the supply is turned on, the laminar power jet is recovered in the output tube as in a typical turbulence amplifier. However, in this case, a portion of the output flow enters the return path as shown in (A) of Figure 8-53 so that it impinges on the power jet as shown in (B) of the figure. The return flow causes the power jet to become turbulent with the resulting decrease in the output pressure. This causes the flow along the return path to decrease or stop so that the power jet regains laminarity and the cycle repeats itself.

8.4.8.5 Tuning Fork Fluidic Oscillator - This precision oscillator (Figure 8-54) consists of a temperature compensated tuning fork, a load sensitive fluidic flip-flop, control transmission lines, and a feedback transmission line. The supply stream emerges from an aperature in one tine (control) of a tuning fork and is alternatively switched to the two downstream channels as the control tine oscillates. The two downstream channels provide control inputs to the load sensitive flip-flop which oscillates accordingly. One fluid pulse train from the flip-flop is fed back and impinged on the driven tine of the tuning fork so as to maintain oscillation of the fork at its natural frequency. The other flip-flop output is used as the output signal of the oscillator. Since the oscillator uses the air pulse only to apply sufficient energy to the tuning fork to sustain oscillation, it is insensitive to variations in the speed of sound of the working fluid.

Although hybrid in nature, the tuning fork oscillator offers such an extremely accurate frequency reference that it should not be overlooked. This device has a frequency accuracy of $\pm$ 0.002 percent at room temperature and $\pm$ 0.05 percent over a temperature range of -35 to +200°F, when operated at 400 cps. The tuning fork itself is temperature compensated by the use of special alloys, heat treatment, or bimetal construction. The trend in this type device is toward small high frequency tuning forks, since higher frequencies result in smaller amplitudes and better accuracies.

8.4.9 Moving Part Devices

Fluidics is generally associated with control and logic systems operating at low power levels, whereas ordinary moving part devices are thought of in terms of controlling power functions. With the advent of fluidics, numerous moving mechanical part devices have become available to perform control functions. Although most of these are industrially oriented, they may prove useful in aerospace applications where low quiescent power drains are required and where it is simply impossible or uneconomical to operate fluidic elements because of limited space, weight, and energy. Moving part devices are also useful in hybrid fluidic systems to boost a low pressure signal (a fraction of a psi) to a useful working pressure i.e., sufficient to operate a valve actuator. These power interfaces can be either gas to gas, gas to hydraulic fluid, or even gas to liquid propellant interfaces.

8.4.10 Fluid Interfaces

The bulk of present fluidic applications are of the hybrid variety in that transducers are required to interface with other modes of control. Very little original work has been done to develop new devices in this area, and most of the available interface components are adaptations of commercially available hardware for hydraulic and pneumatic control.

8.4.10.1 Electrical to Fluid Transducers - In an electrical to fluidic (E-F) transducer, an electrical signal produces a mechanical movement of an element into the active area of a fluidic device. There is a wide variety of these E-F transducers in general use. For example, an E-F transducer for on-off or digital operation can be a solenoid valve and for proportional control a torque motor driven flapper valve. Several E-F transducers of this type are shown in Figures 8-55, 8-56, and 8-57. The torque motor driven E-F transducer has a bandwidth of about 300 cps and the bandwidth for the piezoelectric ceramic disc E-F transducer is between 1000 to 2000 cps.

Practical E-F transducers have been made which utilize the secondary effects of acoustic power, i.e., acoustic streaming and radiation pressure (References 15, 16, 17). For example, a turbulence amplifier can be made to switch to the NOR condition by means of sound waves. The device shown in Figure 8-58 utilizes an electrically induced magnetic field to position or oscillate a

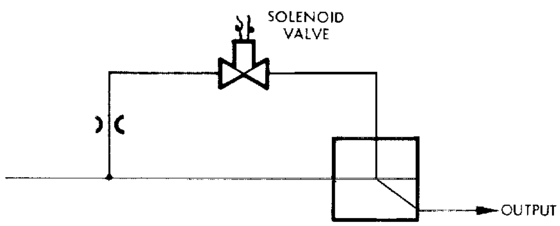


Figure 8-55. Solenoid Valve E-F Transducer

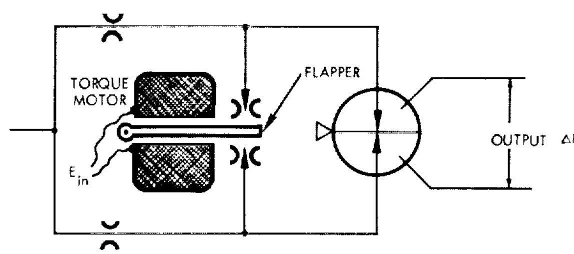


Figure 8-56. Torque Motor Driven E-F Transducer

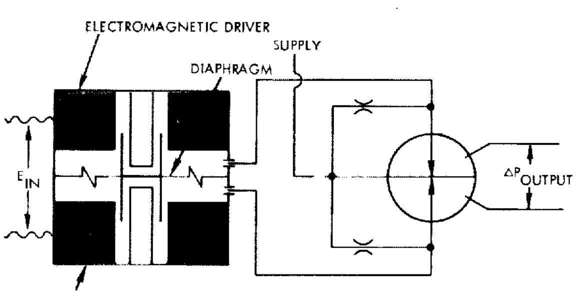


Figure 8-57. Piezoelectric Ceramic Disc E-F Transducer

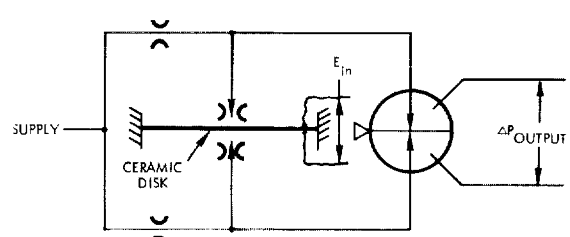


Figure 8-58. E-F Transducer-Diaphragm Oscillator Type

diaphragm which varies the differential pressure across a fluidic proportional amplifier. A piezoelectric ceramic disc can also be used in place of the electromagnetic driver and diaphragm. Each of these E-F transducers are capable or producing a relatively low pressure pneumatic signal in the range from steady state to about 2000 cps.

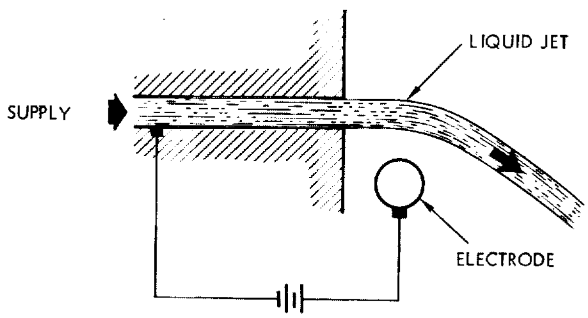
Many new E-F transducers have been devised in which an electrical signal is converted directly into a fluid signal, (References 18, 19 and 20). Heat has also been used to control the separation point in a boundary layer amplifier and to switch the flow in a diffuser. The primary disadvantage in these devices is that considerably more electric power than equivalent pneumatic power is required to operate these devices. A few of these concepts are illustrated in Figure 8-59.

8.4.10.2 Fluid to Electrical Transducers - The most widely used fluid to electrical (F-E) transducers are simple pressure switches, pressure transducers, and hot wire probes. Most pressure switches and many pressure transducers are limited to application in systems with a bandwidth of less than 100 cps because of the additional transducer volume involved. Flush mounted, piezoelectric pressure transducers and the newer semiconductor strain gage elements (0.10 inch sensing diameter) are capable of operating in components with bandwidths in excess of 20,000 cps. Thermistor or hot wire probes have also been installed in the control and output channels of fluidic devices to indicate the presence or absence of flow.

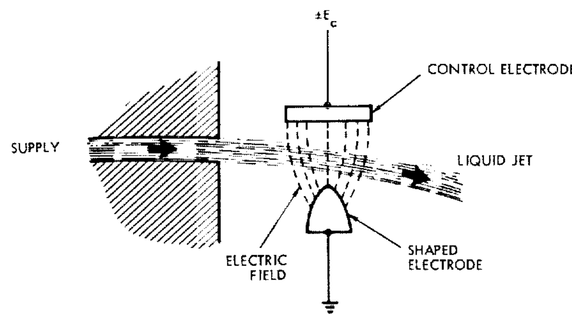
Heater elements or hot films can be installed in the output ducts of a proportional amplifier and connected in a bridge circuit as shown in Figure 8-60. The bridge output voltage is then proportional to the differential cooling of the two sensors by the output flows. Another type of differential E-F transducer utilizes a small semiconductor or wire strain element mounted between the output legs of a proportional amplifier as shown in Figure 8-61. This transducer will produce a sensitive and accurate output signal directly proportional to the amplifier differential output pressure. Both of these devices are capable of bandwidths better than 20,000 cps, depending on how they are installed in relation to the fluid stream.

8.4.10.3 Mechanical to Fluid Transducers - One of the simplest mechanical to fluid (M-F) transducers is a pressure divider, where the exit is a variable orifice controlled by the operation of a flapper. The flapper can be either a translating member or a rotating cam attached to the mechanical device. Another type of M-F transducer is the interruptable jet which is essentially a turbulence amplifier in which the turbulence inducing element is an object which intrudes into the jet stream. The interruptable jet can sense the mechanical intrusion into the laminar stream with a repeatability of better than 0.0001 inch. For digital circuitry, the concept of the traditional player piano role would permit the use of complex programmed inputs. Another version of this concept uses standard punch cards as the input signal or programming device.

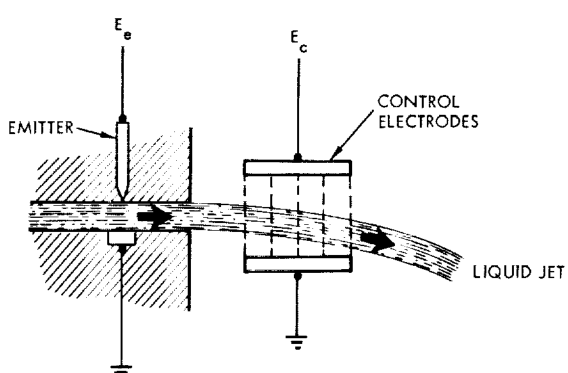
Analog fluidic systems require a differential pressure signal at the interface between the transducer and the system input. The M-F transducers shown in Figure 8-62 are conceived to perform this function. In devices A, B and C the output nozzles (P_1 and P_2) are each supplied from a constant



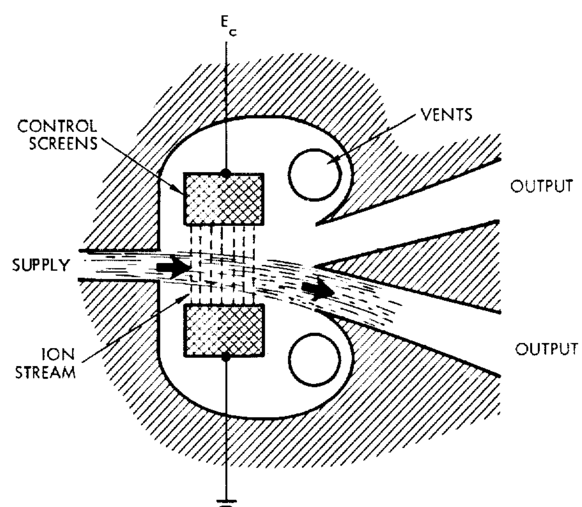
a. Free Jet Deflection by Coulomb Attraction



b. Free Jet Modulation by Non-Uniform Field

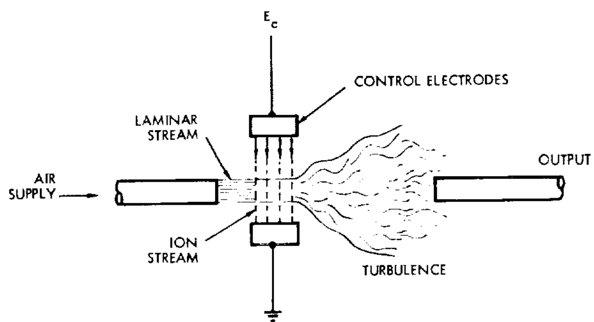


c. Charged Free Jet Deflection by Linear Field

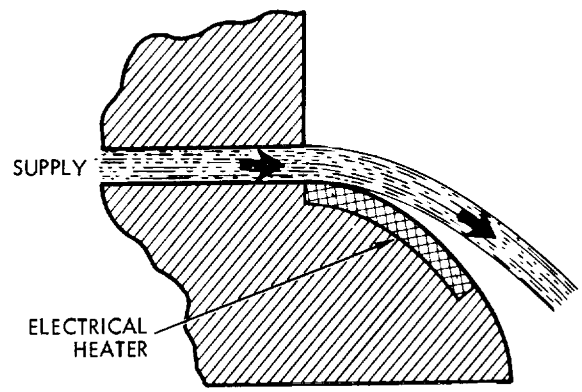


d. Submerged Jet Modulation by Ion-Drag Interaction

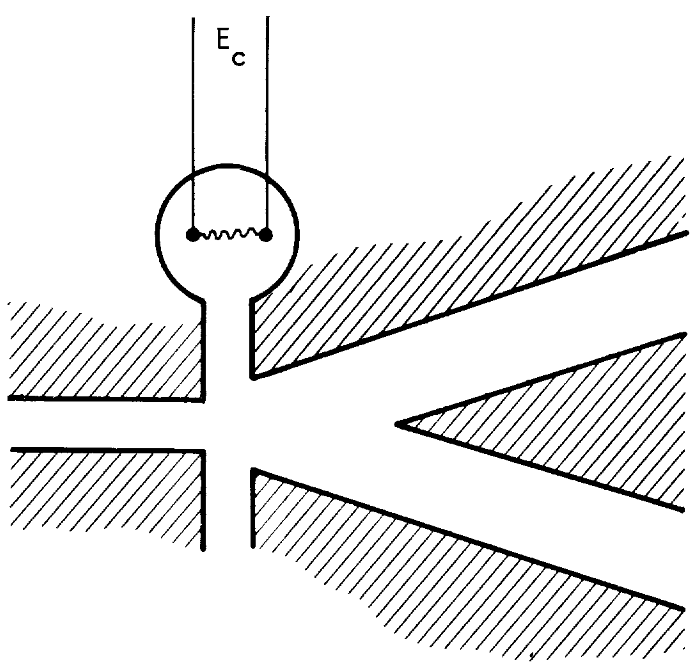
Figure 8-59. E-F Transducer Experimental Phenomena



e. Turbulence Amplifier Control by Ion-Drag Interaction



f. Controlled Separation by Heat Addition



g. Bistable Device Switching by Spark Discharge

Figure 8-59. E-F Transducer Experimental Phenomena (Cont.)

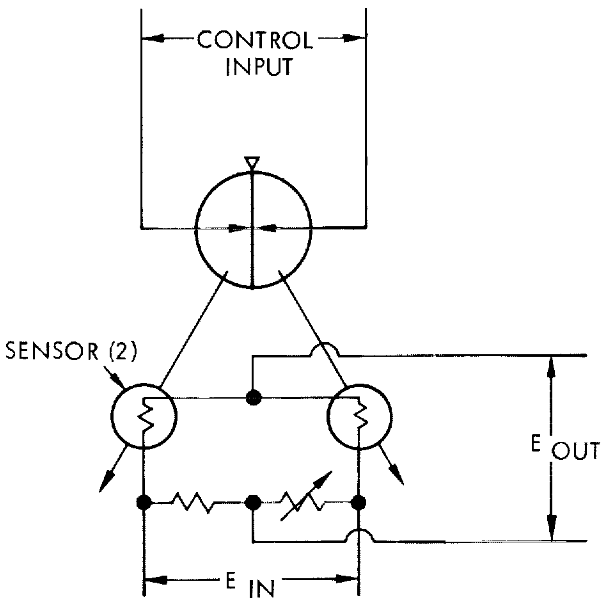


Figure 8-60. F-E Transducer - Hot Film Type

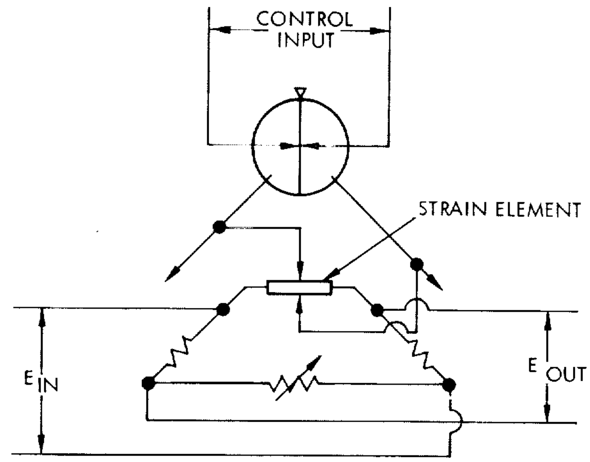


Figure 8-61. F-E Transducer - Strain Element Type

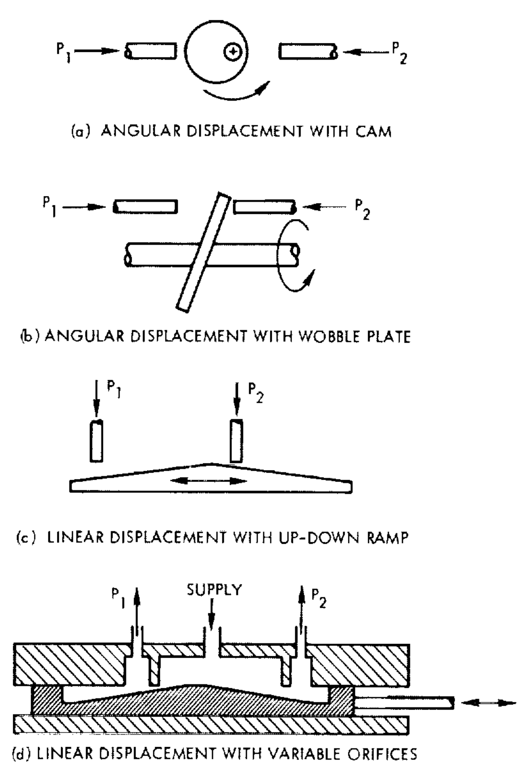


Figure 8-62. M-F Transducers - Differential Type

pressure source through a choked orifice. As the displacing member moves closer to one nozzle and further away from the other the resulting changes in back pressure are reflected in the differential pressure signal P_1 minus P_2. The transducer in D functions in a similar manner, except that the change in orifice area is accomplished within the transducer itself.

8.4.10.4 Fluid to Mechanical Transducers - Fluidic devices provide a relatively low output pressure which can be amplified fluidically or can be used directly to drive or operate a variety of devices. These devices are generally adaptations of existing pneumomechanical devices, for example, a fluidic signal may be used to position a spool valve in a power circuit. Other typical applications would be the control of a valve with a diaphragm, piston, or a geared gas turbine actuator.

8.4.11 Fluidic Sensors

The sensing of system variables is fundamental to all control functions. The output of a sensor is a function of a system variable such as temperature, position, angular rate, or acceleration. Whether a device is called a sensor, an interface element, or a transducer is often a matter of opinion or definition. For example, many of the M-F transducers discussed previously could be called sensors because they sense the physical position of an object and provide an output which is a function of the sensed position.

The available information on fluidic sensors is rather scarce because the devices are either classified or proprietary in nature. The following devices are representative of the sensors which have been reported in the current literature and those which are novel in terms of fluidic principles.

8.4.11.1 High Impedance Pressure Sensor - Pressure signals are normally sensed directly by fluidic circuits. However, in some situations the fluid producing the control input data may be toxic, corrosive, dirty, or hot so that it may not be desirable to have the fluid enter the fluidic circuit. This is especially true where continued exposure to external contamination could render a system inoperative or where human exposure to a toxic exhaust gas could be harmful. The high impedance pressure sensor provides a means by which pressure levels can be detected without flowing the sensed media into the sensor (Reference 21).

The high impedance pressure sensor (Figure 8-63) is essentially a bistable wall attachment amplifier with a bypass channel from the supply to one control port. This control port is designated as the control input and the opposite control port is then designated as the bias input. When the supply fluid is turned on, some fluid is bypassed in the control input channel where it impinges on the far wall causing the stream to split as shown in Figure 8-64. A relatively small portion of the stream is entrained by the power jet in the interaction region and the remaining portion is discharged through the control channel. A bias input is adjusted to cause the power jet to initially attach to the opposite or right wall. When the control input is restricted by either a physical blockage or a control signal of the proper magnitude, the power jet will switch to the left output port (Figure 8-65). A variable bias resistor is used to adjust the sensitivity of the sensor

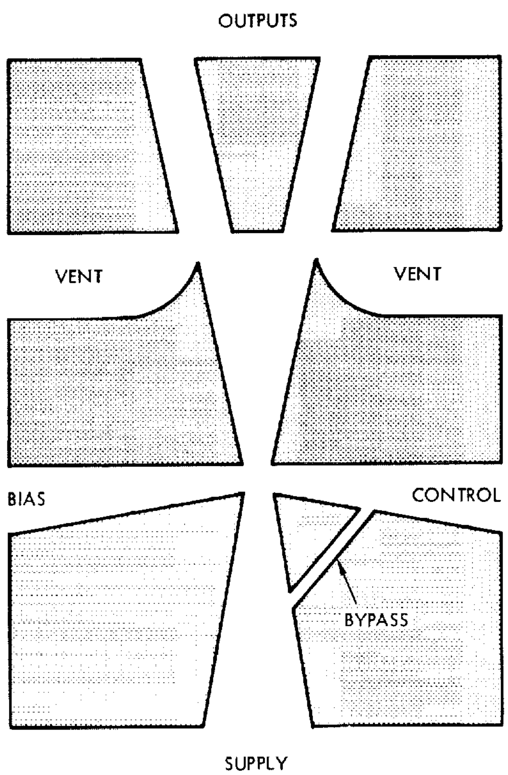


Figure 8-63. High Impedance Pressure Sensor

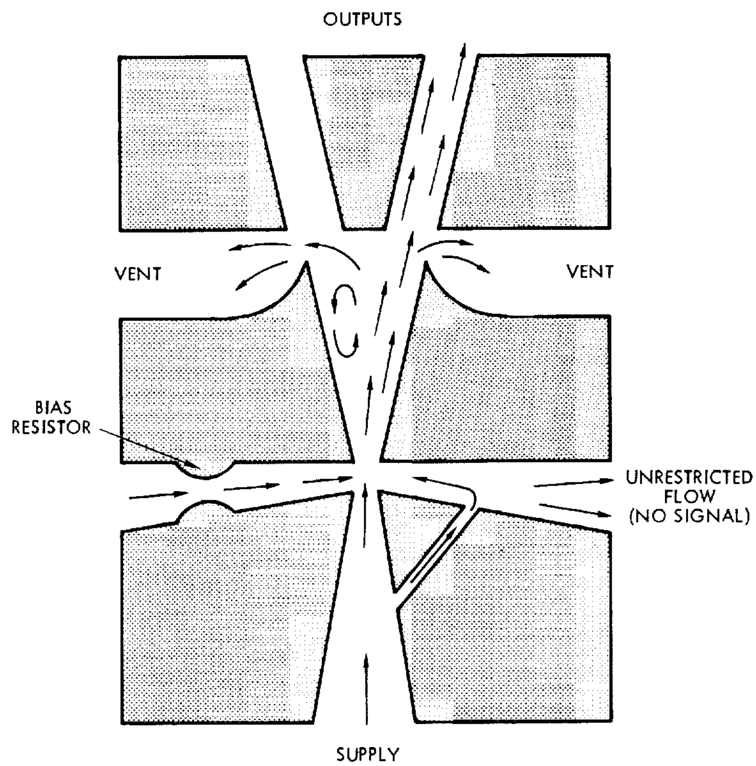


Figure 8-64. High Impedance Sensor With No Control Signal

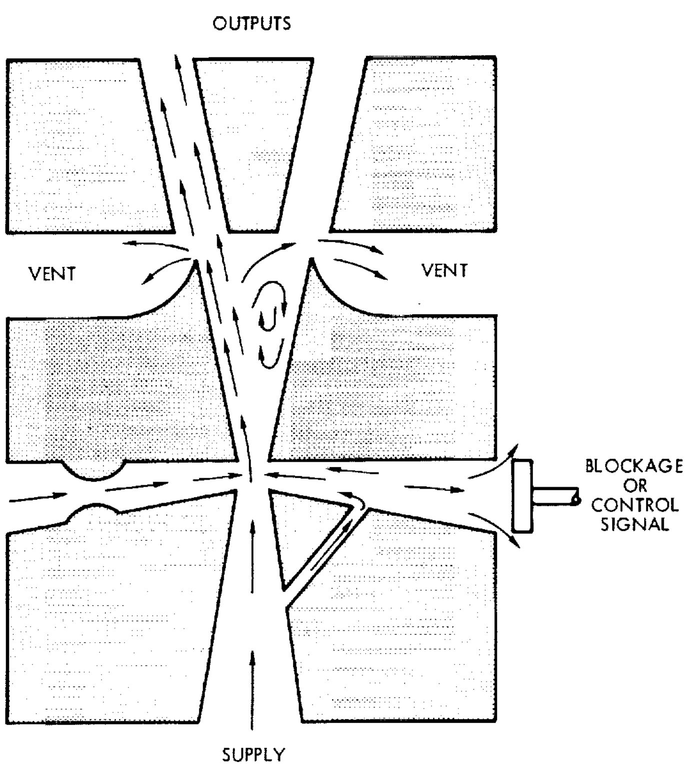


Figure 8-65. High Impedance Sensor With Control Signal

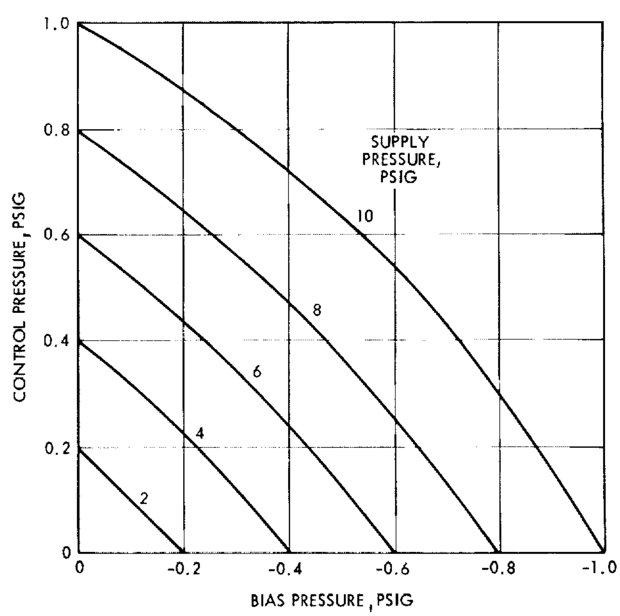


Figure 8-66. Pressure Sensor Control or Switching Pressure

and consequently the control pressure level at which the supply stream switches (Figure 8-66).

The pressure sensor can be modified for use at high altitudes or in outer space as shown in Figure 8-67. This is accomplished by interconnecting the vents and the bias input and discharging the flow through a common orifice. The sensor will then function independently of atmospheric back pressure provided the vent pressure is high enough to choke the vent orifice.

8.4.11.2 Temperature Sensors - Several types of external feedback fluidic oscillators have been developed for measuring gas temperature (References 22, 23 and 24). Although many of these vary in configuration and design, their basic operation depends on the fact that the acoustic velocity in the external feedback path is a function of gas temperature (Figure 8-68). Therefore, if the switching time for the active fluidic element (wall attachment flip-flop) in the oscillator is assumed to be zero, the oscillator frequency is:

$$F = \frac{u_c}{2\ell}$$

where: F = frequency, cps
u_c = acoustic velocity of the gas, m/s
ℓ = length of the conduit, m

Theoretically, the oscillator temperature sensor will operate in virtually any environment as long as the minimum flow velocity necessary for operation is maintained. The temperature range for a given device is determined by the liquification temperature of the working gas at low temperatures and the melting point of the sensor material at elevated temperatures.

Oscillator temperature sensors are built by Minneapolis-Honeywell in sizes ranging from 1/4 x 3/8 x 0.09 inches thick to 2 x 2 x 1/2 inches thick which operate from about 17 kilocycles down to 2 kilocycles, respectively. A calibration curve for a typical 2 x 2 inch sensor is shown in Figure 8-69. The supply pressure must be sufficient to start and sustain the sensor oscillation, normally 3 or 4 psig. Ultimate sensor accuracy is about $\pm 0.2\%$ which is achieved after the sensor exit nozzle is choked. The sensor has a response time of less than 1 second. Signal to noise ratio varies from 5 to 20 depending on the inlet pressure.

8.4.11.3 Vortex Rate Sensor - A typical vortex rate sensor is shown in Figure 8-70. Supply fluid flows through the inertial coupling element, through the vortex chamber, and out to vent. The coupling element is usually a porous material but uniformally spaced vanes have also been used.

When the angular rate is zero, supply fluid passes through the coupling ring and flows radially through the vortex chamber and out the vent. When an angular rate is imparted to the sensor, a tangential velocity is induced in the supply fluid by the coupling element which is amplified in the vortex chamber due to the conservation of angular momentum. This increased velocity is detected with an aerodynamic pickoff located in the vent tube.

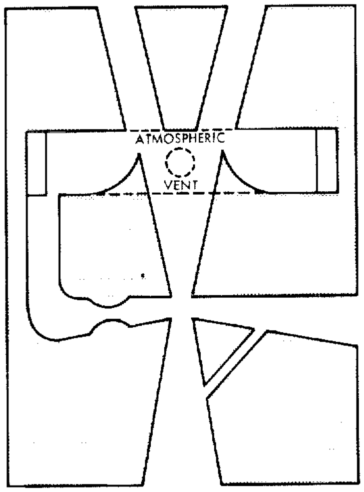


Figure 8-67. Pressure Sensor for Space Operation

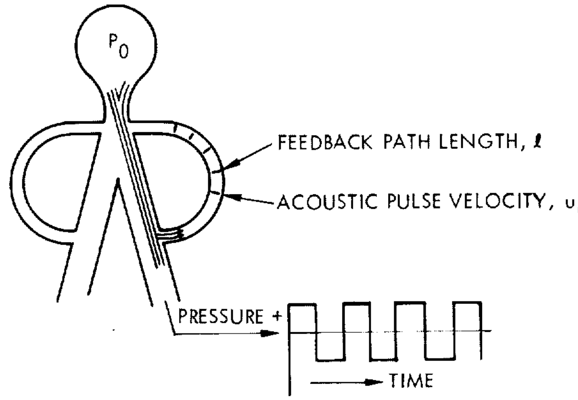


Figure 8-68. Fluidic Oscillator Temperature Sensor

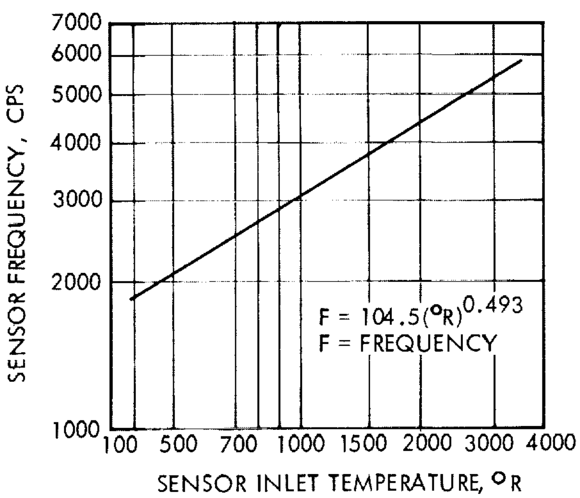


Figure 8-69. Temperature Sensor Calibration Curve

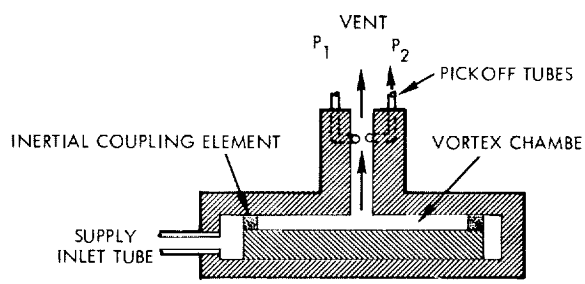


Figure 8-70. Vortex Rate Sensor

Table 8-5. Vortex Rate Sensor Characteristics

Diameter:	4.0 in.
Supply Pressure:	20.0 psig
Flow Rate:	150 cc/sec
Gas:	air
Sensitivity:	0.02 psi/deg/sec
Transport Time:	20.0 msec
Noise Amplitude:	0.002 psi

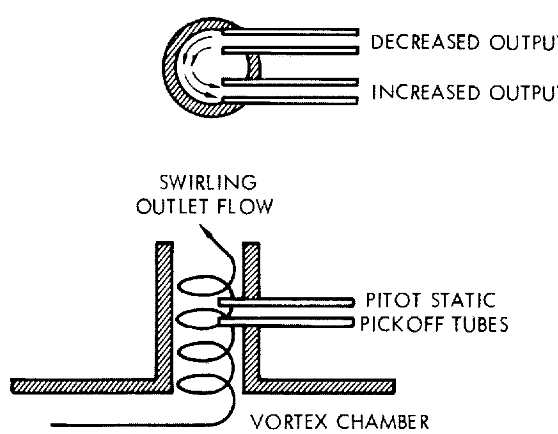


Figure 8-71. Rate Sensor Aerodynamic Pickoff Tubes

The pickoff (Figure 8-71)senses angular rate by measuring the vorticity imparted to the outlet flow, i.e., the pressure differential generated across the pickoff tubes is directly proportional to the applied angular rate.

The performance characteristics for a typical vortex rate sensor are summarized in Table 8-5. One of the many varied applications anticipated for the vortex rate sensor is its utilization in fluidic missile control systems. Other applications are in experimental phases and range from missile attitude control to light aircraft controls.

8.4.12 Fabrication and Materials

8.4.12.1 Component Considerations - Fluidic devices can be made by a wide variety of manufacturing processes and in almost any type of rigid material. Techniques for the fabrication of these devices are well known and not difficult. The most important consideration is that the performance and characteristics of a fluidic device are closely related to its geometric shape, so that in fabricating fluidic devices intricate shapes must be held to precise dimensions.

The size of fluidic devices varies widely because of the many different types and also because of the different uses for the same device. For example, fluidic elements used as logic gates in aerospace applications are miniaturized to minimize power consumption, whereas a similar device used as a switch to divert flow in a pipeline is much larger. Because of this wide diversity in the size required, quantities involved, tolerances required, and materials used, there is no singularly best fabrication technique for fluidic devices.

Manufacturing processes in common use include the casting, thermoforming, photoetching, and molding of plastics; chemical milling, photoetching, electrical discharge machining, electroforming, die casting, and powder metallurgy of metals; and photoetching, ultrasonic machining, and electron beam machining of ceramics. This listing is only representative of the wide range of choices available.

The environmental tolerance required of a fluidic element is the primary consideration in the choice of material. Fluidic devices must have sufficient strength to withstand both structural and hydraulic forces without undue distortion. Surface hardness of the material must also be considered, particularly if the working fluid carries abrasive particles. Wear in stream-interaction devices is critical in the nozzles and on the splitter. Other factors, such as operating temperature and compatibility with the working fluid, also enter into the selection.

Injection molding of thermoplastic materials appears to offer the cheapest method of fabricating large quantities of fluidic elements. However, these elements are limited to operation at near room temperature conditions and with noncorrosive media. In industrial applications, injection molded devices should provide long term reliable operation, particularly in digital systems.

There are several fabrication methods which are suitable for two-dimensional elements for aerospace applications. The important methods are discussed below.

8.4.12.2 Compression Molding - This is perhaps the most economical production method for manufacturing parts from thermosetting materials. Tolerances can be held as close as required for most fluidic elements. Fillers are used to add stiffness, control shrinkage, and reduce the coefficient of thermal expansion. Maximum operating temperature is about 400°F for the best filled thermosetting plastic elements, and filled epoxy elements are limited to about 300°F.

8.4.12.3 Photoetching Ceramics - This process was originally developed by the Corning Glass Works to prepare substrates for electronic circuits and has been adapted to the manufacture of fluidic elements. A high contrast negative is placed upon a thin sheet of Fotoform glass, which is a silicate glass containing a photosensitizing ingredient such as the cesium radical, Ce^{+3}. In the presence of ultraviolet light, the exposed glass absorbs the ultraviolet radiation, creating a contact print in depth. The glass is then heated to about 1200°F so that colloidal particles of crystallized lithium metasilicate appear as a white opal image, which is formed in the exposed areas of the glass. When the glass sheet is immersed in a hydrofluoric acid bath, the exposed areas dissolve 20 to 30 times faster than the clear unexposed areas of the glass.

Further processing converts the Fotoform glass to a higher-strength partially-crystalline material called Fotoceram. The finished Fotoceram elements offer several important advantages which are normally associated with ceramic material, i.e., high dimensional stability, low moisture absorption, good shock resistance, and operating temperatures approaching 1000°F. This process can produce intricate two-dimensional elements down to a nozzle width of 0.005 inch. An important consideration in circuit fabrication is that both the Fotoform and Fotoceram plates can be thermally laminated to form a monolithic structure.

8.4.12.4 Photoetching Metals - This process has recently become very important in the manufacture of fluidic elements for aerospace applications. Essentially the process removes metal by the chemical etching of preferentially exposed surfaces. The process is presently limited to metal sheets no thicker than about 0.020 inch, because the dimensional tolerances that can be achieved increase with increasing metal thickness. A 0.005 inch wide channel can be etched through a 0.001 inch thick stainless steel with a tolerance of 0.00025 inch or about ± 5 percent. This same 0.005 inch wide channel would have a tolerance of ± 20 percent if etched in a 0.005 inch thickness of the same material.

In the fabrication of two-dimensional fluidic elements, several laminations of etched sheets are required to provide the required aspect ratio. Photoetching can be used with the following metals (presented in the order or increasing difficulty): copper, nickel, carbon steel, stainless steel, aluminum, titanium, and molybdenum. Operating temperature depends primarily on the metal used and the method selected for sealing the laminated sheets.

8.4.12.5 Other Fabrication Methods - Many new methods are being considered for the fabrication of fluidic elements. Techniques such as electron and laser beam machining may eventually make it possible to pack 1000 fluidic elements in one cubic inch. Coining techniques may soon make it possible to manufacture interconnected fluidic elements by indexing a die and stamping in the right location. However, much work still needs to be done in the sealing of fluidic elements, particularly those for use with high temperature working fluids. To date, diffusion bonding and furnace brazing have been used with moderate success in the sealing of photoetched metal elements, but more efficient sealing methods are required if the inherent reliability of fluidic elements is to be achieved.

8.4.12.6 Integrated Circuits - The interconnection of fluidic elements with fittings and tubing is neither practical nor reliable enough for aerospace circuits. One trend in aerospace systems is to group circuit elements on a functional basis in rectangular or circular two-dimensional planar arrays or modules (Figure 8-72). This allows the incorporation of the maximum number of interconnections within the module. Power supplies, vent connections, and interconnections between modules can then be accomplished by interspersing manifolds between the modules (Figure 8-73). The number of circuit modules that can be stacked is limited because the supply and exhaust ports as well as the circuit interconnections must all be ported through the stacked circuit blocks, and a point of diminishing returns is eventually reached.

Another method is to bring all the connections out to the edge of the module. Modules can then be stacked on edge in between manifolds which provide the fluid power supplies and circuit interconnections. As shown in the physical concept of a rocket engine fluidic controller (Figure 8-74), this makes for a convenient arrangement in that sensors, interfaces, and compensating volumes can be located close to the circuit modules.

For smaller fluidic circuits it may be more convenient to fabricate the manifold and interconnections in a single block (Figure 8-75). Then the fluidic elements, sensors, and interfaces are externally attached to the manifold block. This method is more convenient for prototype applications and allows the modification or replacement of circuit elements when required.

8.4.13 Test Equipment

8.4.13.1 Introduction - A fluidic control system for aerospace application should contain several sensing, computation, and control actuation functions as shown in Figure 8-76. The block diagram indicates that some system instrumentation will be self contained, i.e., designed in as an integral part of the control system itself and used for both operational instrumentation and ground test. Inputs are also provided for diagnostic instrumentation and for the fluid or electrical perturbation of the system during ground test.

An important criteria for sensors and the techniques selected for checkout of a fluid control system is that pertinent test data should be provided without disturbing normal system operation. The sensors must of course

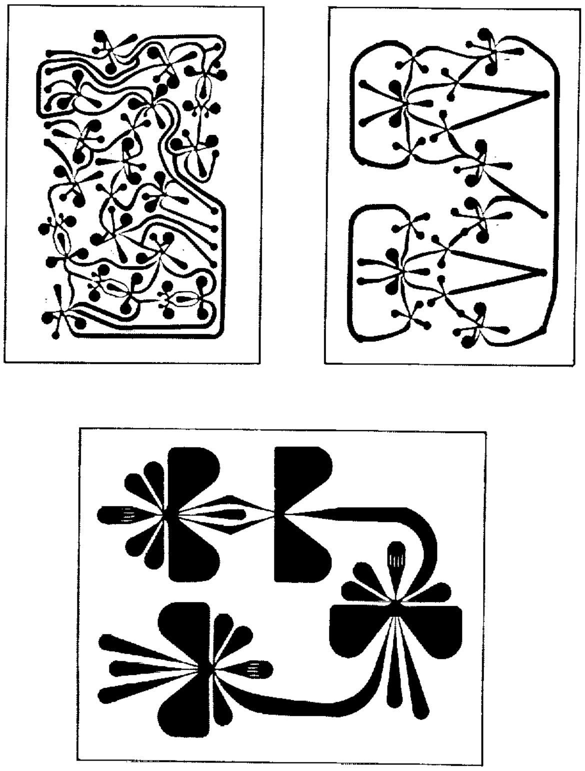


Figure 8-72. Silhouettes of Circuit Modules-Planar Arrays

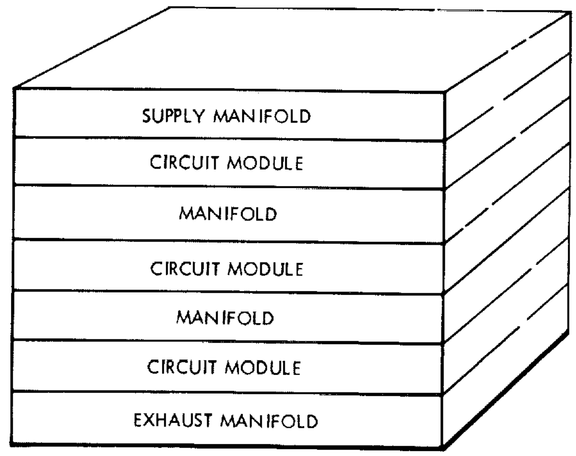


Figure 8-73. Stacked Integrated Fluidic Circuits

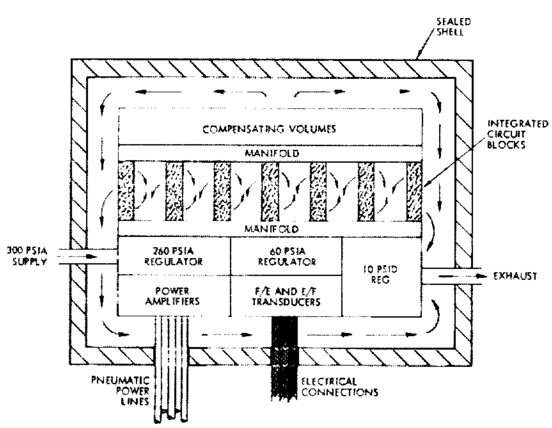


Figure 8-74. Physical Concept of Nuclear Rocket Controller

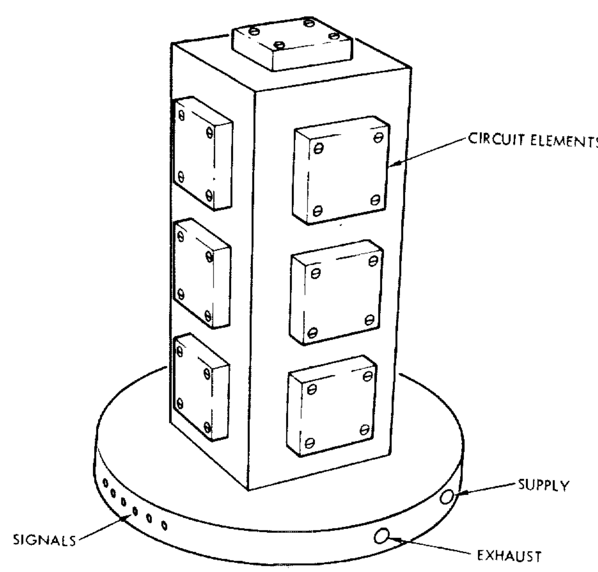


Figure 8-75. Single Manifold Integrated Fluidic Circuit

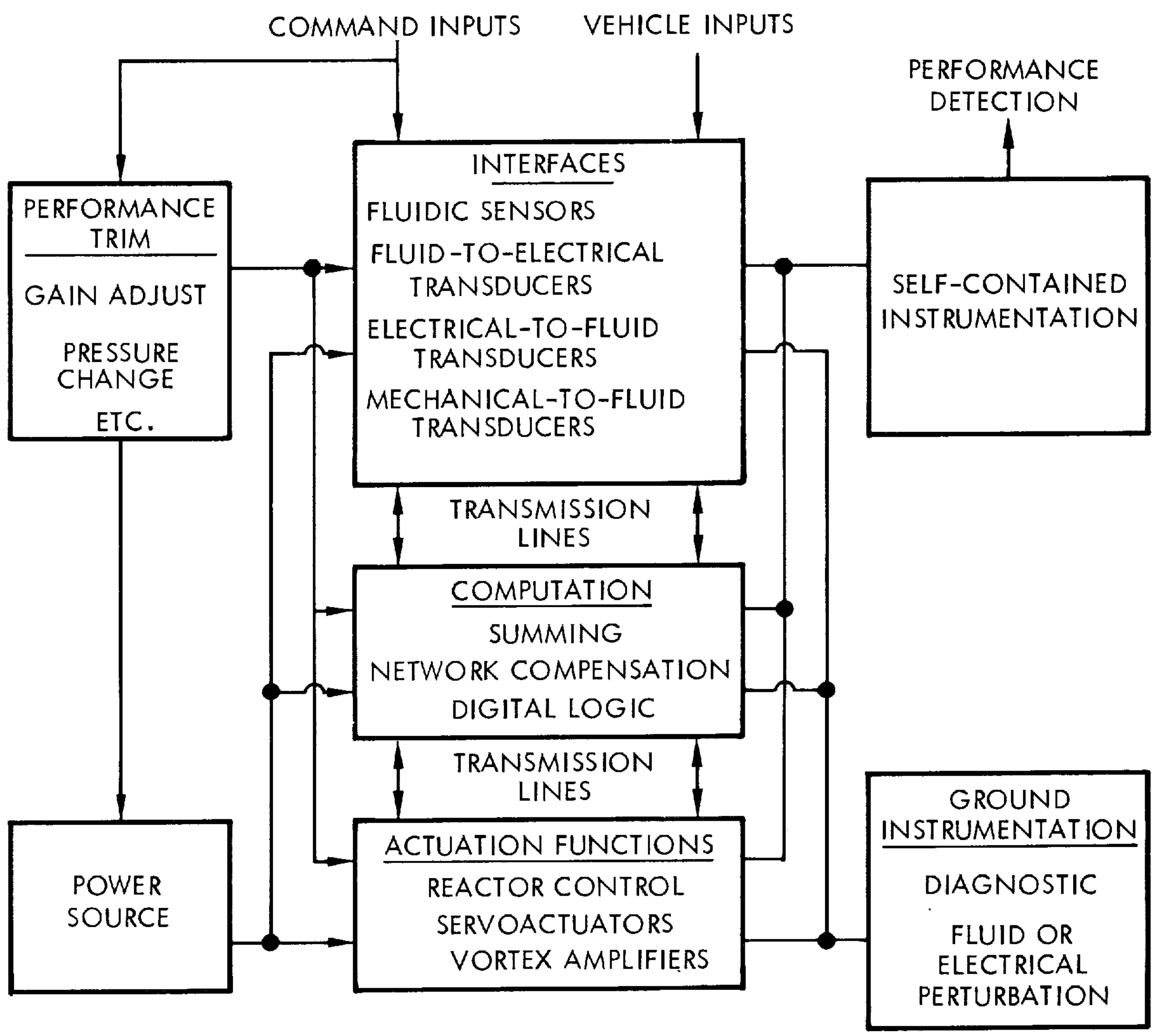


Figure 8-76. Fluidic Control System Concept

be simple and should not require the physical dismantling of the system for installation and should not compromise inherent reliability of the system. Self contained instrumentation must be capable of prolonged service in the system operational environment.

8.4.13.2 General Test Equipment - An excellent source of information regarding general test equipment for use in the evaluation of fluidic circuit is the Aerospace Component Designers' Handbook (Reference 8). Subsections 5.15 Instrumentation, 5.16 Pressure Switches, and 5.17 Flowmeters, are of particular interest. The instruments utilized in the fields of aerodynamics and thermodynamics can also be used directly for the checkout of fluidic systems, particularly for steady state pressure and flow measurements. In addition, many of the E-F and F-E transducers discussed previously can also serve as excellent means of perturbating and monitoring a fluidic system during ground test.

8.4.13.3 Specialized Test Equipment - The specialized test equipment applicable to the checkout of a fluidic system include (1) constant temperature anemometers, (2) thermistor sensors, (3) miniaturized semiconductor pressure transducers, (4) quartz pressure transducers, and (5) miniaturized pressure switches. These devices are discussed in detail in Reference 8.

8.5 FLUIDICS DESIGN CONSIDERATIONS

Fluidics offers several appealing advantages to aerospace systems, including no moving parts, environmental insensitivity, simplicity, and ruggedness, all of which make for high reliability expectations. Other considerations are potential weight and volume savings and to a lesser degree reduced system fabrication costs. The latter considerations are qualified by whether the comparison is with conventional fluid power controls or with electronics.

From a practical standpoint, the most important points are:

1. Any pressurized fluid (such as stored gas) combustion products and liquid propellant can be used as a power source in a fluidic system. If it can eliminate the need for electric power, this is a distinct advantage.

2. In systems where parameters such as pressure, flow, temperature, and angular rate are sensed and used as control signals, fluidics senses and utilizes these signals without conversion into mechanical motions as would be required in conventional controls.

In considering the aspects of fluidic design, the problems and limitations of fluidic applications are discussed along with important application criteria and typical subsystem applications. Useful sources of component and system design information are referenced and possible methods of formal analysis are reviewed.

8.5.1 Problems and Limitations

8.5.1.1 Significant Development Requirements - Government agencies are particularly interested in the problem areas relative to the aerospace application of fluidics. A recent survey performed by them listed the following problem areas as the most significant in order of importance:

1. Fabrication
2. Environmental Testing
3. Interfaces
4. System Techniques
5. Standard Modules
6. Reliability

The significant problem areas and future development requirements determined from literature and patent searches and agency interviews are summarized below:

1. The effects of temperature on the performance of fluidic elements need to be identified for design purposes.

2. Although many fluidic elements operate equally well on gases and liquids, very little developmental effort has been expended on elements specifically designed for operation with liquid.

3. The scaling of fluidic elements is a major problem, particularly when going from laboratory models to miniature sizes.

4. More compatible electrical to fluid and fluid to electrical transducers are required. Many of the current devices utilize a mechanical interface which detracts from the reliability of the transducer. In addition, excessively high expenditures of electrical energy are required for operation of the devices.

5. Several passive circuit elements are required, including a wide range laminar flow restrictor, a series capacitance, an efficient nonvented fluid diode, and a sharp cutoff low pass filter.

6. Performance information is needed on fluidic elements exhausting to space vacuum or a controlled back pressure.

7. Consideration needs to be given to shutoff functions and power supplies with no moving parts.

8. An optimum size and arrangement for fluidic circuit modules needs to be considered.

9. Materials, fabrication, and interconnection techniques need to be established which are particularly suited to spacecraft propulsion components.

10. Analytical design procedures are noticeably lacking.

11. Since present estimates are misleading, production runs are necessary to provide insight into the reproducibility of fluidic elements and their ultimate cost.

12. Service data are required on fluidic elements and systems before realistic reliability estimates can be made.

8.5.1.2 Operational Problems - Fluid filtration, power source performance, and element interchangeability are the areas in which operational problems are most frequently encountered. Conventional 10 to 40 micron (nominal) filters have been found adequate for most applications; however, in atmospherically vented circuits, care must be taken to avoid the aspiration of contaminants from the environment. The use of liquid propellants in fluid circuits necessitates other considerations, such as propellant compatibility, rheopectic or thixotropic behavior, and contamination of the environment. Many available power sources do not deliver a constant-pressure supply, and component selections and the circuit design must compensate for this. Only conventional mechanical pressure regulators are available at the present time, but fluidic pressure regulators are expected in the future. Monopropellant gas generation systems and closed cycle power supplies hold the answers for future aerospace applications.

Unless absolutely necessary, miniature devices with small nozzle dimensions must be avoided to ensure low sensitivity to variations in operating conditions, fabrication, and contamination. Many new fluidic element designs are less sensitive to geometry variations, and manufacturing techniques are also being improved constantly. Instrumentation is presently inadequate; consequently, it is difficult to verify system performance and, more important, to pinpoint malfunctions. Concentration on satisfying the need for special-purpose instrumentation should help; however, in the long run, the most promising solution is self-contained miniaturized instrumentation.

8.5.1.3 Analytical Techniques - Earlier development and a large percentage of the current development of fluidic elements and systems have been done on an empirical basis, although current macroscopic mathematical models have provided useful results. This reflects the difficulty of mathematically analyzing device steady-state operation and the even more formidable problems encountered in representing dynamic phenomena. Major efforts are underway in industry, government agencies, and universities (notably MIT and Penn. State) to formulate and to commit to practice the tools and techniques required to facilitate the analytical design of fluidic components and systems.

8.5.1.4 Fluidic Device Problems - The formation of an analytical model is complicated by the fact that fluid flow phenomena are sensitive to several interrelated variables. For example, wall attachment amplifier performance is influenced by many factors which include Reynolds number, the ratio of control jet velocity to power jet velocity, several aspects of element geometry, size, surface roughness, upstream perturbations, and downstream loading. The complete determination of a suitable model will require a better understanding of turbulent jets and interaction flows. Only very crude models resulting from the use of simplifying assumptions are available in most cases. Marked improvements in fluidic technology should result when it becomes possible to readily solve the partial differential equations for turbulent fluid flow.

Jet and solid surface interactions, the solution of pressure and velocity transients, and the stability of a free jet in the presence of acoustic disturbances are examples of critical problems which need to be solved in order to optimize device design.

8.5.1.5 System Design - With all fluidic elements, it is necessary to cope with similar considerations in order to achieve successful interconnection into circuits and systems. These considerations include: the effects of nonlinearities and dynamics in active and passive circuit elements and in connecting passageways; loading due to temporary and permanent instrumentation; noise generation, propagation, and amplification; temperature and pressure sensitivity; and impedance matching at critical places. When these considerations are ignored, instabilities may occur, signals may prematurely saturate, energy may be wasted, and excessive stages of amplification (with the accompanying complications of noise amplification) may be needed. Accordingly, small changes in element and line geometries, mean operating pressures, or mean flow rates in lines and passages can cause significant changes in performance.

Obtaining optimum system performance requires a compromise between gain, stability, and response time. Each fluidic element must be carefully matched to its load to obtain maximum signal power transfer and to provide sufficient signal power to drive successive stages. Besides providing maximum power transfer, the matching of line and port impedance minimizes the reflection of waves at the junctions of lines and ports and reduces the likelihood of premature saturation. In general, fluidic device static pressure flow curves are very useful in achieving proper matching. Approximately linear operation is usually achieved for small swings about a chosen operating point. The dynamic response characteristics are such that for a small device, static performance can be assumed up to about 400 cps.

Power supply regulation and reliability are necessary prerequisites to proper system performance. Fluid supply lines should be large enough to avoid excessive losses. If the flow area of supply lines and connectors is too small, undesirable pressure drops can occur so that supply pressures at individual element power nozzles will be less than specified. The most serious consequence of small flow areas is the greatly increased loss in each bend and fitting due to eddies and turbulences which lead to greater losses in straight sections.

In the design of analog systems:

1. Problems exist in matching component characteristics because of the inherent load sensitivity of analog devices and because of the variation of component characteristics with operating point.

2. Noise is a major problem, particularly in high gain circuits where staging is required and the noise is generated in the first or second stage.

3. Most systems are nearly proportional; i.e., the fluidic elements operate at a frequency and output level continuously related to the input signal, so that there are no discontinuities and only very slight amounts of higher harmonics in the output signal.

4. Carrier techniques including both AM and FM can be applied to minimize problems of noise, drift, and bias in critical applications.

Regarding digital system design:

1. Early advances were achieved by means of cut-and-try developmental work, leading to empirical results. Theoretical work has not yielded many results that are directly useful in design.

2. Digital elements are normally less sensitive to noise and load conditions than corresponding analog elements.

3. Interstage matching of element characteristics is not as critical as for analog systems.

4. Vented digital amplifiers are the most widely used in digital circuits. However, a vented circuit may not be the best choice where maximum power transfer is desired (such as in most aerospace applications).

8.5.2 Application Criteria

8.5.2.1 Performance with Various Fluids

Gases - The gases commonly available in aerospace systems include ram air, pressurants, propellant boiloff, and combustion products. Any of these gases may be used as a working fluid for fluidic devices. Particulate contamination, such as metallic particles can cause erosion in fluidic elements, particularly when in hydrogen and helium, because of the high sonic velocities. Ice crystals formed from impurities such as water vapor and carbon dioxide in the gases can clog orifices and filters. Normal care to ensure that systems are clean and dry combined with the use of adequate filters (usually 10 to 20 micron nominal rating) should obviate most problems.

Gases such as hydrogen, helium, and high temperature combustion products are notoriously difficult to seal and will often leak through exceedingly small openings such as are found in connectors and static seals. Once a leak starts, the erosive effects of these gases can be quite significant. Boiloff gases from oxidizers such as N_2O_4 and LF_2, as well as most combustion products gases, are highly corrosive and adequate provisions must be made to ensure compatibility with construction materials. Monopropellant hydrazine gas generator systems supply a relatively clean gas which should find wide application as a working fluid for fluidic systems.

Liquids - Water, hydraulic oils, and virtually any liquid propellant (including cryogenics) may be used as the working fluid in a fluidic system. In most cases more serious problems are encountered with liquids than with gases, primarily because of difficulties with materials compatibility and the lack of design data and elements for liquid operation. As with gases, cleanliness of liquid flow media must be maintained to avoid problems. Of particular significance is the case of cryogenic fluids that may become contaminated with gases whose freezing points are higher than the storage temperature of the cryogenic fluid.

The development of gaseous fluidic systems has progressed much more rapidly than liquid systems. Although fluidic elements can be successfully operated with any of the liquid propellants, present component configurations were designed for gas operation, and consideration must be given to redesigning elements for liquid operation. Liquid elements are slower to respond than similarly-sized pneumatic elements, and higher density working fluids require higher input power for system operation. Also, dissolved gases tend to come out of solution in the low pressure regions formed at abrupt changes in cross section or direction. Small elements pose other problems which can be related to the flow regime required for proper operation. Some elements require either laminar or turbulent flow conditions to perform their function while others rely on a laminar to turbulent transition. A specific element tested with air and then with hydraulic fluid showed that supply pressures of 0.2 and 360 psig, respectively, were required to attain the same Reynolds number for the two cases.

Gelled Propellants - Both metallized and nonmetallized gels are characterized by thixotropic properties; i.e., the viscosity decreases with increasing shear rate and stress decreases with time at constant shear. As the gel flows through lines and components, the shear becomes greater, the viscosity becomes less, and the gel behaves more like a low viscosity liquid.

Gelled propellants, especially metalized gels with metal particle sizes ranging from 5 to 50 microns, are obviously not applicable to miniaturized fluidic systems. In addition, the properties of gelled propellants can present several problems in larger fluidic devices. Pressure drops through lines and elements are higher than those of comparable liquids and are unpredictable because the viscosity varies. Flow through nozzles can cause evaporation of the liquid phase of the gel, which leaves a solid matrix as a residue which can hinder or restrict the flow. The abrasive action of metal particles can cause erosion of nozzles and passages. The compatibility of gelled propellants with the materials of construction is generally comparable to the base liquid propellant.

8.5.2.2 Operating Temperature - Fluidic devices can be made to operate with some fluids at any given temperature, limited only by the materials available for construction. Elements have been operated with liquid hydrogen, and a vortex valve has been operated with 5500°F working fluid (Reference 25). Digital elements can be operated over broad temperature ranges; however, analog devices are quite sensitive to temperature variation. This sensitivity is caused by such things as viscosity variations, sonic velocity changes, and orifice and nozzle size variations because of thermal expansion or contraction. Differential circuits can be used to compensate for small temperature changes, and temperature sensitive gain changing networks are required for compensation over broad temperature ranges.

8.5.2.3 Operating Pressure - The primary problems anticipated with high pressure levels are structural strength and seals. The minimum pressure requirement of state of the art computational elements operating with gases is about 0.5 to 10 psig. Where required, digital logic can operate successfully at 0.1 psig or less. Power elements operating on liquid have been tested at pressures up to several thousand psig. Back pressure regulation or a constant pressure sump may be necessary to maintain acceptable Reynolds numbers if elements are required to operate over a wide range of ambient or vent conditions. For elements operating on gases, overall pressure ratios seldom exceed 1.3 to 1.

8.5.2.4 Response Time - The response time of fluidic elements refers to the time delay between the application of a step input signal and the time at which the resulting output signal reaches a level which is 63 percent of the final value. Response time of a specific fluidic element is primarily influenced by the transport time of a fluid molecule through the device. With gases, this transient time is normally figured to be equivalent to a velocity of 1 inch per millisecond.

State of the art response time of small fluidic elements operated on gases is presently about 1 millisecond. An important consideration is that the response time of most fluidic elements increases as fluid density increases.

This is illustrated in Figure 8-77, where it can be seen that liquid-operated elements tend to be an order of magnitude slower than gas-operated elements. The figure also shows that elements will operate faster as they are made smaller.

8.5.2.5 Power Requirements - Fluidic elements require a continuously flowing supply of working fluid for normal operation so that, in logic control circuitry, the individual component supplies can add up to a sizeable power drain. For power functions in applications with low duty cycles and long missions, fluidic elements consume a little more power than conventional control components. Power consumptions should be considered carefully even if a plentiful supply of working fluid, such as gas turbine or rocket engine bleed gas, is available. If a stored gas supply is required for the fluidic systems, the power drains of fluidic logic and analog elements should be in the low milliwatt range.

Power consumption in state of the art fluidic computational devices ranges from 0.02 to several watts of fluid power as shown in Figure 8-78. One example of the new low-power logic indicated in Figure 8-78 is the two-dimensional laminar NOR amplifier (Section 8.4.6.3) which was developed at the Harry Diamond Laboratories.

The most logical approaches to reduce power consumption are miniaturization and reduced supply pressure. Extreme miniaturization (below 10 mil widths) compromises element reliability and complicates element and circuit fabrication. This justifies the present trend toward lower supply pressures.

8.5.2.6 Operating Life - The actual required operating life of a fluidic element can vary from a few cycles to several hundred thousand cycles depending on mission requirements. Since there are no moving parts that can wear out, the operating life of an element is not usually a problem. The most significant effects on operating life are materials compatibility, seals, erosive action of the working fluid, and the environment.

8.5.2.7 Leakage - For a basic two-dimensional fluidic element sealed with a cover plate, consider the leakage paths across the seal layer. In a cold gas or liquid system some leakage can be tolerated across the seal without adversely affecting component performance. However, in a hot gas system even minute leaks can cause severe erosion in the seal layer which will soon develop into a large leak and ultimate component malfunction. Nonvented leakage of this type is generally hard to detect unless it is external to the component vent ports. Manufacturing techniques and careful inspection of seals during component assembly are perhaps the best methods of maintaining the integrity of the seals. As in conventional fluid systems, leakage can result in severe loss of fluid media, fire and explosions, and, in some cases, toxicity hazards to personnel.

8.5.2.8 Signal to Noise Ratio - Noise is defined as the peak-to-peak pressure fluctuations on the signals of a fluidic device so that in high-gain circuits the signal to noise ratio becomes a comparative measure of element performance. Of primary concern are element geometry, fabrication method, and operating conditions.

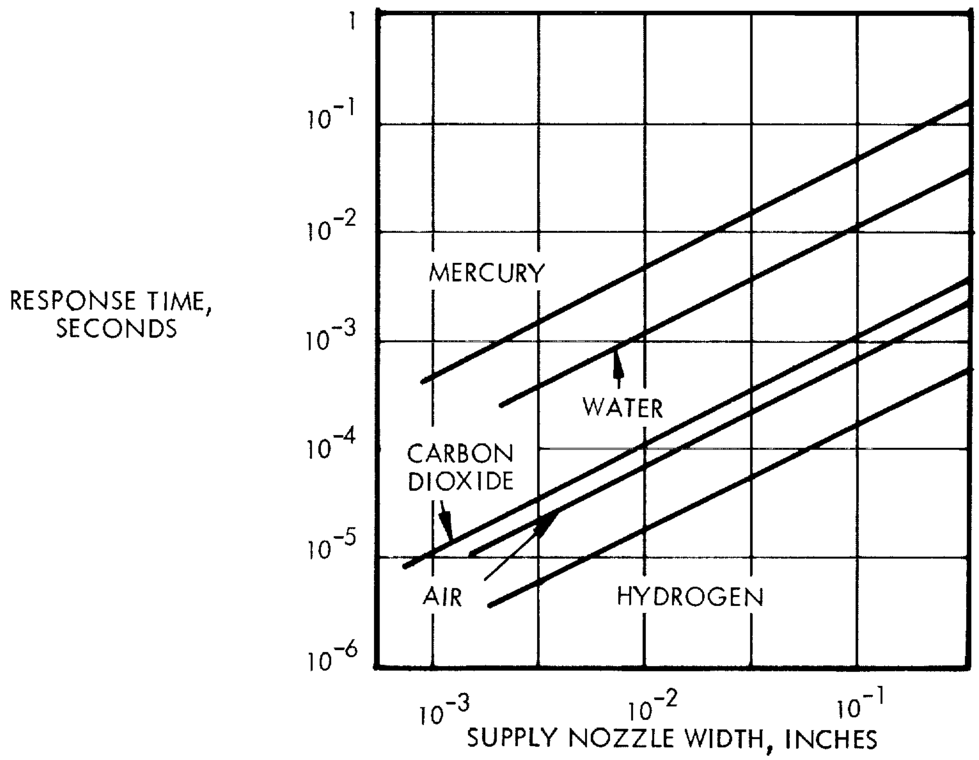


Figure 8-77. Component Response Times with Various Fluids

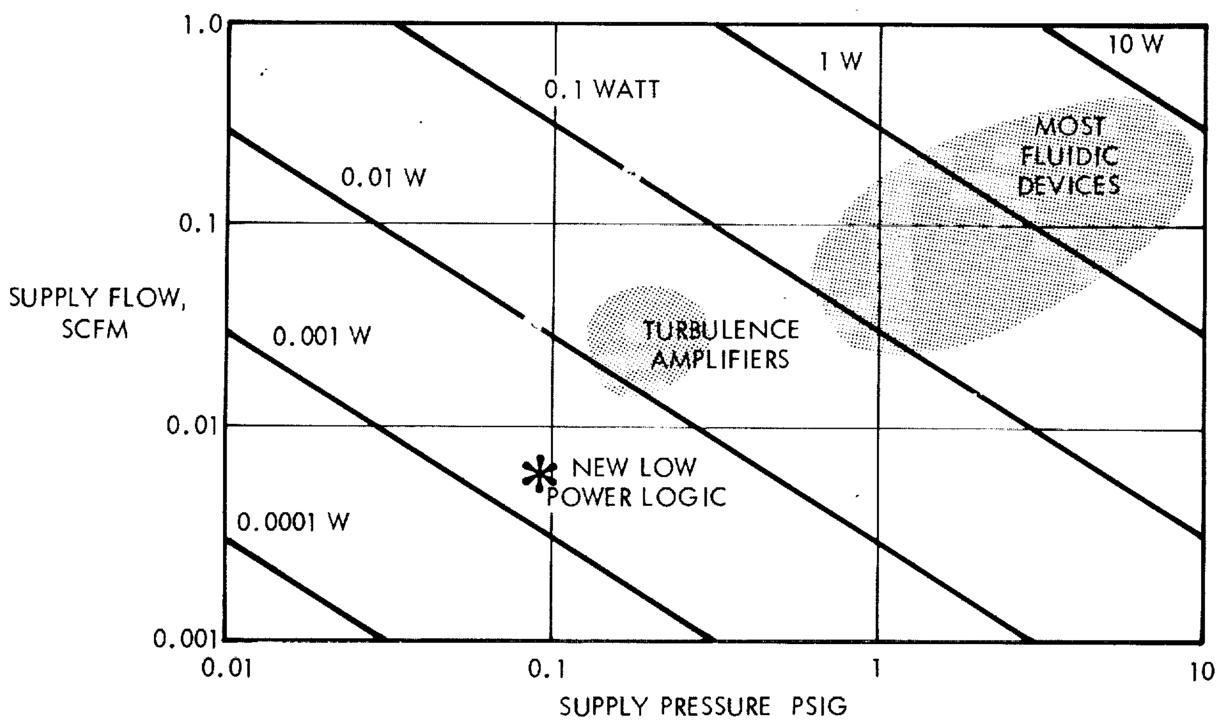


Figure 8-78. Power Consumption of Fluidic Devices

There are several fluidic elements potentially capable of operating with relatively high signal to noise ratios (>200). Some element geometries are much noisier than others; however, these devices are generally of the digital variety. The turbulence amplifier is particularly susceptible to external vibration and shock, and the edgetone amplifier generates considerable internal noise since the device is purposely designed unstable to enhance switching speed.

8.5.2.9 Sterilization - Complete sterilization of all components on a spacecraft may be necessary for planetary missions or flyby missions to the planets. One method of sterilization involves a soak at temperatures up to 300°F for 60 hours, which is repeated for six cycles. A mixture of 12 percent ethylene oxide and 88 percent Freon is also used in a spray for surface sterilization. In a fluidic system, the materials of construction, the methods of fabrication and assembly, and the subsequent handling required must all be considered.

8.5.2.10 Contamination - Fluidic elements can be designed to be contamination insensitive by utilizing large nozzle widths (0.025 inch). For aerospace application this is inconsistent with the normal requirements for low power systems. Therefore, 0.005 to 0.010-inch nozzle widths are considered more practical for gas systems with normal filtration and contamination control during assembly. Estimates as to the smallest practical power nozzle width for liquid-operated systems range from 0.007 to 0.025 inch. The decision on width must be tempered by the required operational life and the fluid properties as well as by the fluid contamination level.

8.5.2.11 Space Maintenance - The maintenance of manned and unmanned spacecraft is a requirement that will involve new designs, techniques, and procedures. In-flight maintenance will be necessary during space travel or in orbiting space stations, and major repairs may be required on vehicles which have landed on the moon or other celestial bodes.

Fluidic elements will not be interchangeable because integrated circuitry should be employed in spacecraft applications. Maintenance or replacement then must be considered on a subsystem basis. The problem then becomes one of the usual difficulties which would be imposed on an astronaut who must connect and disconnect conventional fittings or even specially designed quick-disconnect fittings.

8.5.2.12 Space Environments - The space environment is characterized by radiation, vacuum, zero gravity, and meteoroids. Radiation in space includes the earth Van Allen belts, solar flares and interplanetary radiation. Considering that fluidic elements can be fabricated in stainless steel or molded in ceramics, radiation exposure is not considered a serious problem even for spacecraft orbiting within the Van Allen belts.

Space vacuum is characterized as a low density gas mixture which consists primarily of hydrogen and helium at an estimated pressure of 10^{-16} millimeters of mercury. In this environment the primary problem would be the sublimation or evaporation of the materials utilized in fabricating the fluidic elements. Sublimation is considered negligible for most structural metals, however, metals such as cadmium and zinc have relatively high vapor pressures and should be avoided. High molecular weight polymers such as Teflon are also stable in space vacuum.

Zero gravity should not affect the performance of fluidic elements. In low pressure liquid systems there is a possibility that the wettability of the liquid on the element walls may affect performance.

Meteoroidal hazards to fluidic elements and systems in space must be considered and could possibly exert some influence on design. From a practical standpoint, fluidic elements should be less susceptible to meteoroid damage than components with moving mechanical parts, which could malfunction due to deformation on the inner surfaces resulting from external meteoroidal impingement.

8.5.3 Typical Applications

8.5.3.1 Vortex Amplifier Controlled SITVC - A successful demonstration of a vortex amplifier controlled secondary injection thrust vector control system (SITVC) was made on a NASA Model EM-72 solid propellant rocket motor. This motor is capable of producing approximately 6800 pounds of thrust with a mass flow rate of 30 lb/sec for 13 seconds. The SITVC system (Figure 8-79) produced side forces of up to 4 percent of the main engine thrust level. The vortex amplifiers utilized in this demonstration had the demonstrated capability of modulating a 750 psia, 1 lb/sec flow of 16 percent aluminized, 5500°F solid propellant gas with a demonstrated operating time of 50 seconds. The overall frequency response of the SITVC system showed a phase lag of 28 degrees at about 30 cps.

One method of implementing this type of vortex amplifier controlled SITVC system is shown in Figure 8-80 for a buried nozzle solid propellant rocket engine. In this buried nozzle configuration, the power stage vortex amplifiers modulate combustion chamber bleed gas and inject it directly into the nozzle for thrust vector control. An auxiliary gas generator is required to provide the high pressure gas necessary to control the vortex amplifiers. A similar type of system is possible on a liquid rocket engine (Reference 25).

8.5.3.2 Fluidic Power Amplifier - A prototype fluidic power amplifier has been developed to operate a displacement actuator on a nuclear rocket control drum drive (Reference 26). This power unit utilizes a low level pneumatic input signal and it incorporates frequency variant load pressure feedback. Its output characteristics are similar to those of a four-way open centered servovalve. With no moving parts this power amplifier should be particularly advantageous for operation in cryogenic, high temperature, or radiation environments.

Three fluidic components are used in this fluidic system (Figure 8-81): the vortex amplifier, the jet interaction proportional amplifier and the confined or vented jet amplifier. The pilot stage includes a jet interaction proportional amplifier, an ejector, two confined jet amplifiers, and two summing vortex amplifiers. The two summing vortex amplifiers receive the differential input pressure signal to the power amplifier. Each of the vortex summing amplifiers also contain two control ports which are connected to the load output ports through a frequency sensitive pneumatic filter. The summing vortex amplifiers control the vent flow (and thus the output pressure) of the confined jet amplifiers which provide the differential input signal to the jet interaction proportional amplifier.

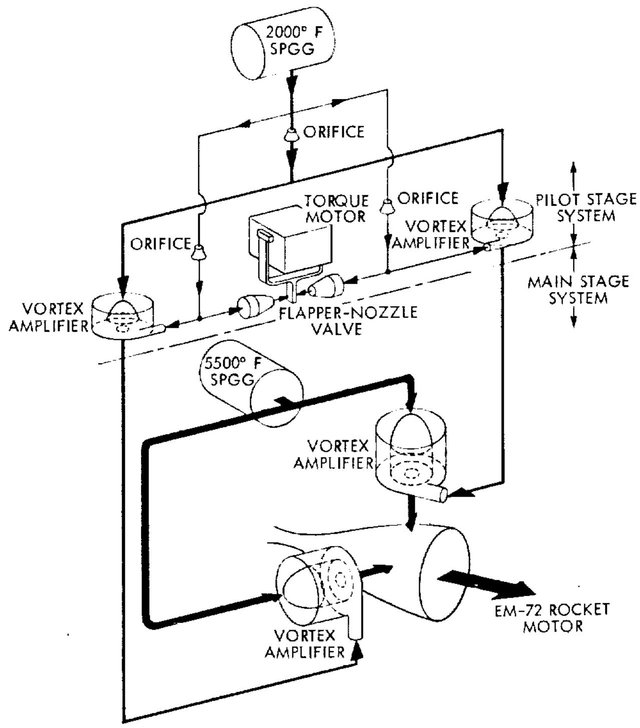


Figure 8-79. Schematic of Vortex Amplifier Controlled SITVC Demonstration System

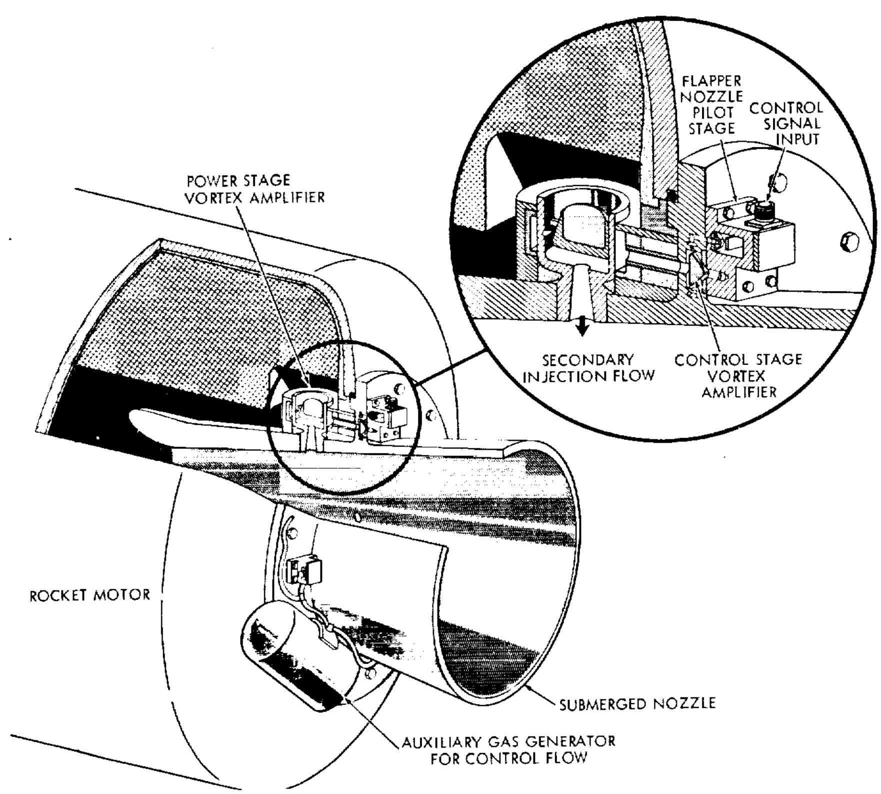


Figure 8-80. Concept of Vortex Amplifier Controlled SITVC System

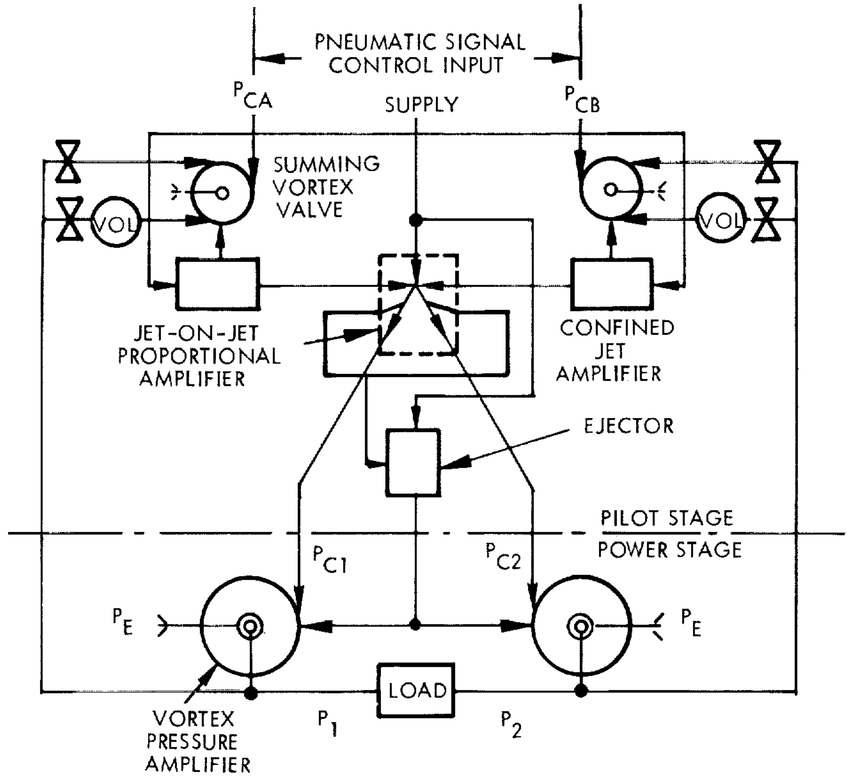


Figure 8-81. Fluidic Power Amplifier Schematic

Table 8-6. Fluidic Power Amplifier Performance With Nitrogen

Item	Power Stage Vortex Pressure Amplifier
1) Supply pressure	148 N/cm^2 (215 psia)
2) Exhaust pressure	34.5 N/cm^2 (50 psia)
3) Flow recovery	50%
4) Rated input signal	10 N/cm^2 (14.5 psia)
5) Input signal pressure bias	53.7 N/cm^2 (76.7 psia)
6) Total input power	10.5 watts
7) Rated no-load flow	3.0 gm/sec (0.0067 psia)
8) Pressure recovery	67 N/cm^2 (98 psi)
9) Linearity-deviation Gain variation	19% 2 times
10) Stability	9 N/cm^2 (13.1 psi)
11) Transient response	0.110 sec 0.190 sec
12) Frequency response Phase shift and Amplitude ratio	20° @ 5 hertz 90° @ 45 hertz $\pm$ 1.7 db
13) Threshold	1%
14) Hysteresis	3%

The outputs of the proportional amplifier differentially control the power stage. To increase the overall flow recovery of the power amplifier the vent flow from the proportional amplifier is recovered by the supply flow through the ejector.

The power stage basically consists of two vortex pressure amplifiers controlled in a push-pull operating mode. An increase in control pressure P_{c1}, reduces the recovered load flow and pressure in one vortex amplifier while a simultaneous reduction in P_{c2} increases the load flow and pressure in the other vortex amplifier. The result is a differential pressure (P_2-P_1) across the load and a load flow depending on the load force requirements.

Performance of the prototype fluidic power amplifier is summarized in Table 8-6, and the output characteristics are shown in Figure 8-82. Predicted performance of an optimized design based on state of the art components is shown in Figure 8-83.

8.5.3.3 TIM Roll Control System - In September 1964, the first successful demonstration of the use of fluidics in a missle flight control system was made. This was accomplished on the test instrumentation missile (TIM) which is a modified version of the Little John Rocket (References 27 and 28). Cold nitrogen gas was used as the power source and supersonic fluidic bistable reaction amplifiers were used as the control moment producers. The stabilization fins on the aft end of the missile were purposely canted to provide a disturbance torque of 5 ft/lb and a roll rate of about 100 degrees per second. During the flight test, the control system operated correctly since the reaction jets were on in a direction to oppose the impressed roll rate. This point was proven by a measured increase in the missile roll rate after the control system supply nitrogen was exhausted.

A schematic of the TIM fluidic control system is shown in Figure 8-84. The power section of the system was controlled by a high-flow dome-type regulator which was activated at launch by a solenoid valve. A combination of proportional bistable and supersonic fluidic devices was used with a vortex rate sensor to form the roll control function. As seen in Figure 8-85, the system utilizes a bistable rate damper with an integrator to minimize the roll attitude drift. Integration is accomplished with a resistor-capacitor combination (first order lag circuit) with a relatively long time constant. The system operated in a limit cycle or bang-bang mode at a frequency and amplitude dependent upon the system's threshold and the time delays of the various components. During the limit cycle, the bistable moment producer output and vehicle acceleration are square waves with a frequency of approximately 3 cps. Vehicle rate is determined by the integration of this wave.

8.5.3.4 Rocket Engine Sequence Control - A fluidic sequence control for a large pump fed regeneratively cooled cryogenic liquid rocket engine was breadboarded and successfully tested with helium (Reference 29). The control system is required to start and shutdown the rocket engine upon command, to monitor the progress of the start, and to activate engine shutoff automatically in the event of malfunction. In addition, a prestart logic circuit ensures that the engine is in the proper state prior to the acceptance of a start signal.

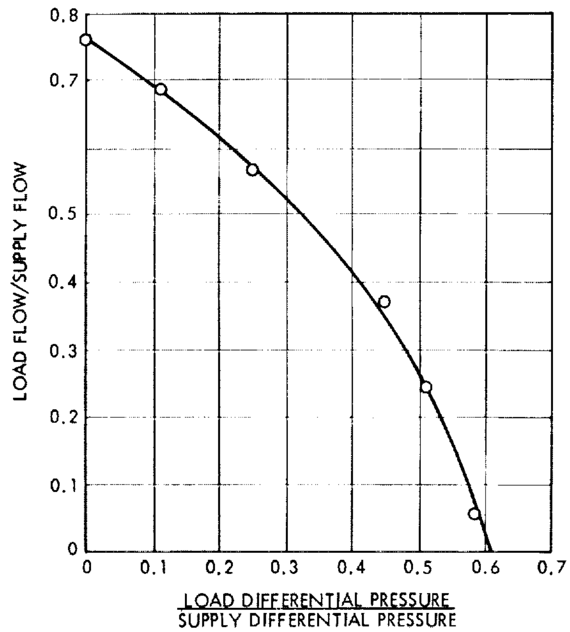


Figure 8-82. Fluidic Power Amplifier Output Characteristics

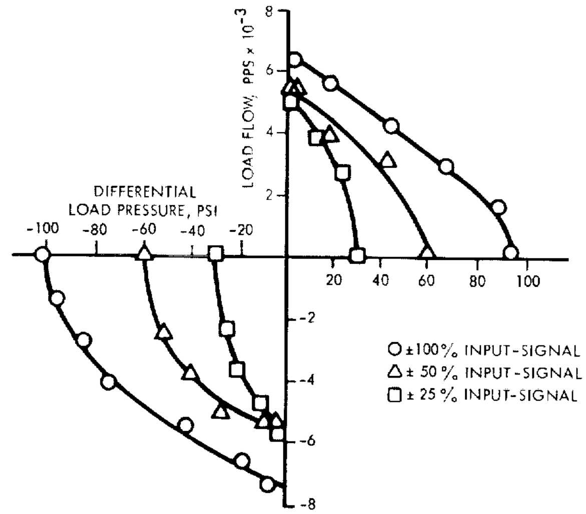


Figure 8-83. Fluidic Power Amplifier Predicted Performance Potential

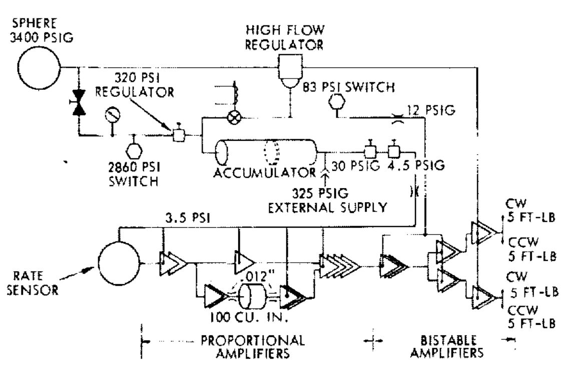


Figure 8-84. TIM Fluidic Control System

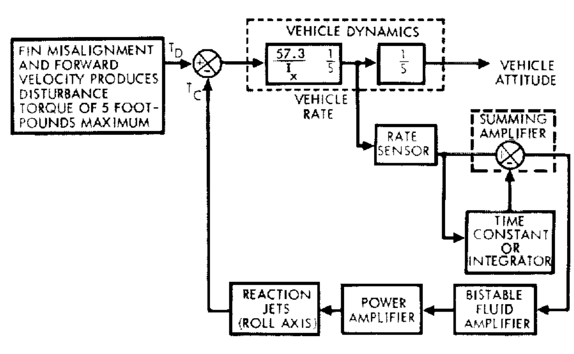


Figure 8-85. TIM Control System Block Diagram

The time based sequence requirements for the sequence control are shown in Figure 8-86. Prior to start, the conditions of the components to be controlled are: the electrical ignition spark exciter system is off; both main propellant valves are closed; the start valve, a valve which controls the application of high pressure gas to the turbines during start is closed; the engine pneumatic regulator is off; and the fuel bypass valve, the valve which bypasses fuel around the thrust chamber cooling tube bundle during the start is open. All valves are pneumatically actuated by four-way valves which are sequenced by the engine controller.

The fluidic sequence control system designed to meet the above requirements is shown schematically in Figure 8-87. It was implemented with 37 OR gates and bistable amplifiers which are used in the timer circuits. The timers are adjustable in the following ranges: 0.2 to 1.0 second, 0.5 to 2.0 second and 2 to 8 seconds with a typical timing accuracy of $\pm$10%. System supply pressure is 20 psig with a nominal supply flow of 5.8 scfm. Although operation of the system was successfully demonstrated, power drains were excessively high. The power drain can be substantially reduced by the utilization of low power logic elements and also by utilizing elements with higher fan-in and fan-out. Alternately, logic elements other than the OR can be used, in particular a passive AND, which will reduce the required number of logic elements.

8.5.3.5 Flight Suit Control System - A prototype automatic temperature control system for liquid cooled flight suits was developed by Honeywell for the Navy's Aerospace Crew Equipment Laboratory (Reference 30). This example is particularly interesting because the fluidic system uses a liquid media throughout. The system incorporates direct sensing and control of skin temperature which is accomplished in each of four zones by the flow modulation and mixing of cold and warm fluid supplies in response to a sensor signal.

The main components of the control system are mounted on a web-like undergarment which the pilot wears under the outer flight suit. The flight suit control system functioned extremely well during tests with a human subject, both at rest and at various levels of activity.

The control system consists of four skin temperature sensors, four fluid control modules, a bias control (for set point adjustment) and the necessary interconnecting tubing (Figure 8-88). Skin temperature sensors and a separate control module is provided for each of four body zones. An external refrigeration unit supplies cold constant temperature fluid to the bias control sensors and control modules. An external heating unit raises coolant temperature (and hence, skin temperature) when the pilots physical activity is too low to supply natural body heat. One main bias control valve changes coolant temperature to all four zones simultaneously. Individual bias valves enable each bias pressure to be balanced against the sensor for a particular zone.

In each zone, the toluene fill of the sensor bulb expands against the valve diaphragm as the skin temperature rises (Figure 8-89). The diaphragm causes the ball to move closer to the valve seat, which drops the pressure at the right control port of the signal amplifier so that

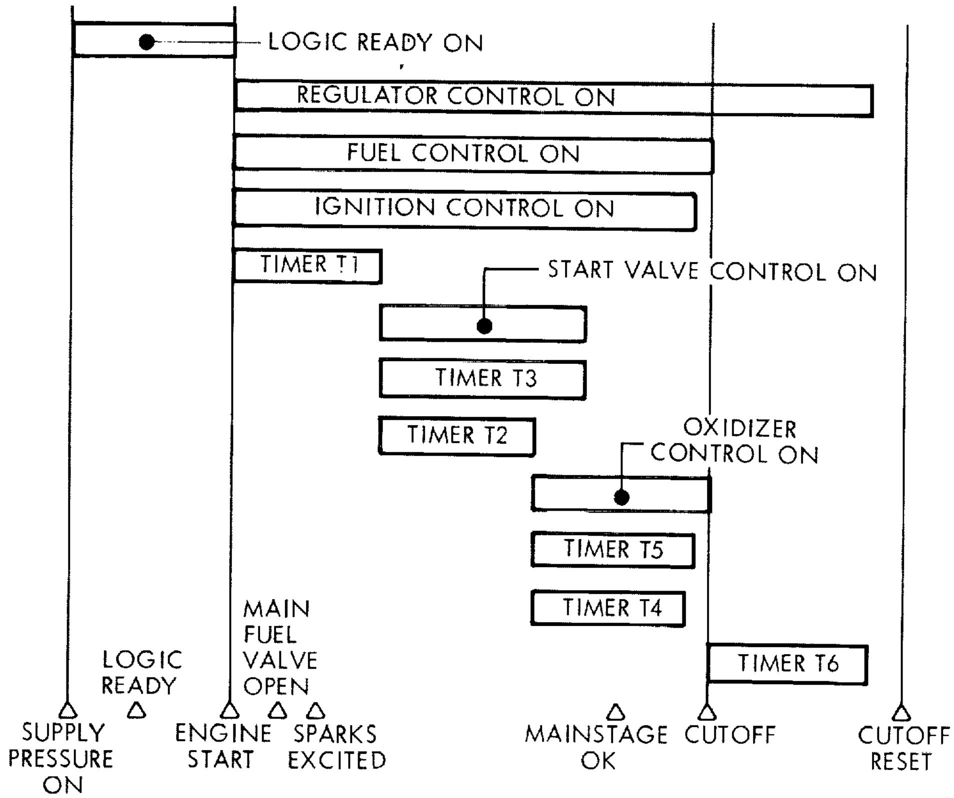


Figure 8-86. Logic Sequence Chart

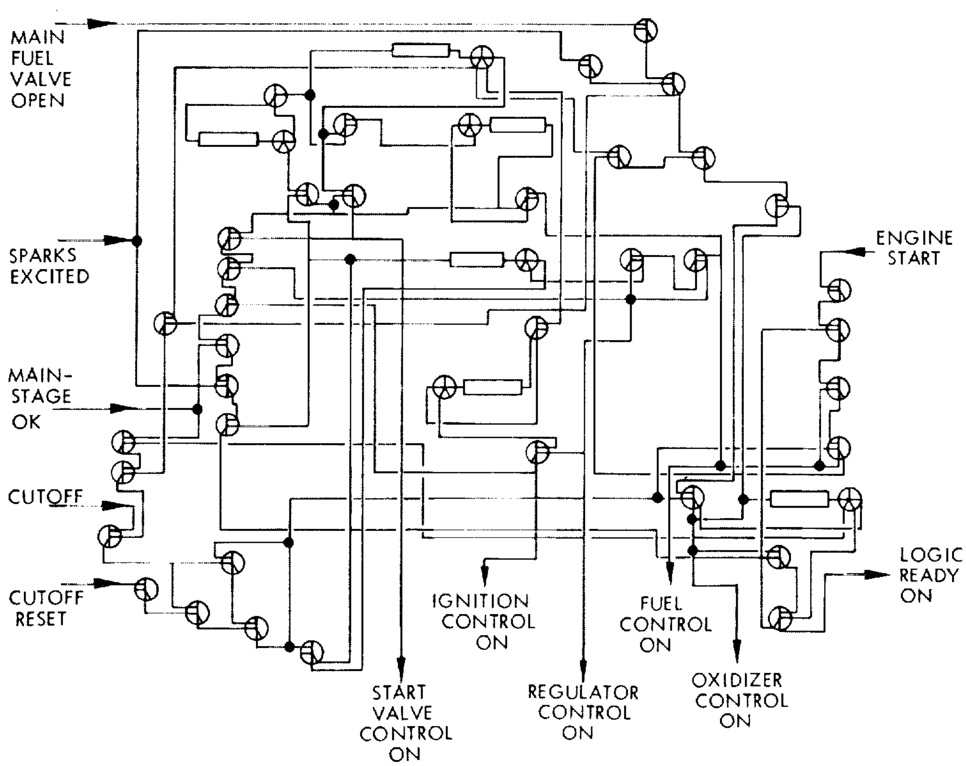


Figure 8-87. Schematic of Fluidic Sequence Control

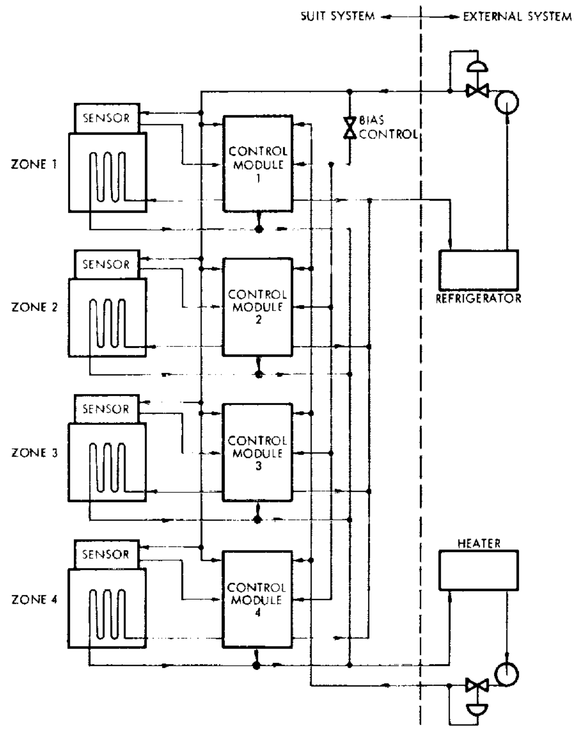


Figure 8-88. Flight Suit Temperature Control System

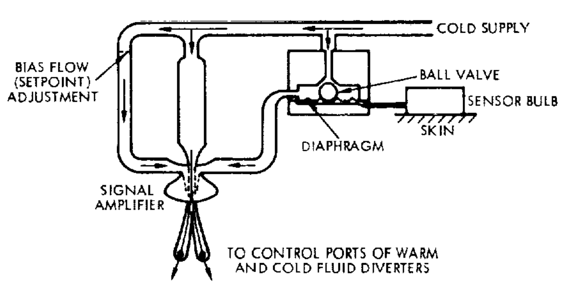


Figure 8-89. Sensor-Signal Amplifier Circuit

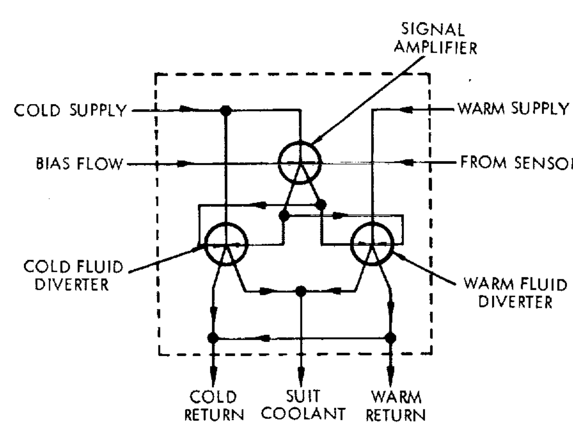


Figure 8-90. Control Module Circuit

the cold fluid flow in the right output leg is increased. This action; i.e., cold fluid flowing into the amplifiers right leg (Figure 8-90), increases the pressure at the respective left control ports of the cold and warm diverters, thus increasing cold power jet flow into the suit coolant line while simultaneously decreasing the warm power jet flow into the suit coolant line. This cools the skin in the control zone area.

8.5.4 Component Analysis and Design

Active and passive circuit elements and components are the least common denominators which are interconnected to form fluidic circuits. Most active fluidic devices have been brought to fruition by cut and try methods and these devices have been tested over a broad range of sizes and operating pressures. Analysis has led to useful empirical formula and design criteria which define the interdependence of the supply and control jets upon each other and their mutual dependence on the interaction region geometry, aspect ratio, output configuration, and loading. Although some progress has been made, the purely analytical design of fluidic components is still a long ways off since only computers can cope with the mathematics involved.

Passive logic elements as well as circuit elements such as restrictors, capacitors, inductors, and interconnecting lines are also required when assembling fluidic elements in digital or analog circuits. The passive logic elements produce no gain, and consequently require no separate power supply. In all these circuit elements, mass flow is considered analogous to current and pressure analogous to voltage. Therefore, a fluid impedance produces a pressure drop as a function of the flow through it.

This section provides reference information to facilitate the design of the basic fluidic elements; i.e., beam deflection, wall attachment, and vortex amplifiers. Information regarding the use of passive circuit elements and an approach to control circuit design is also presented. Computer aided design of fluidic systems based on program solutions on analog, digital, and hybrid computers is also covered.

8.5.4.1 Wall Attachment Amplifier - The parameters which influence the design of the wall attachment amplifier are as follows:

1. Aspect ratio
2. Relative sizes of the supply and control nozzles
3. Set back of the control nozzles
4. Set back, angle, and length of the attachment wall
5. Length of the interaction region
6. Location and shape of the splitter
7. Location and area of the vents
8. Output area
9. Relative area and location of the output and vents

Detailed information regarding the effects of varying the above parameters is available in References 31 and 32. Additional useful information is available in References 33 through 36.

The size of a wall attachment device is established by the width of the power nozzle; i.e., a 10 mil element refers to one which has a power nozzle width of 0.010 inches. Logically then, all of the internal amplifier dimensions are then defined as ratios of the power nozzle width. Considering that most wall attachment elements are two-dimensional, the depth of the element profile is then expressed as the aspect ratio, which is the ratio of the profile depth to the power nozzle width. Fluidic devices are normally designed with aspect ratios from 1 to 4.

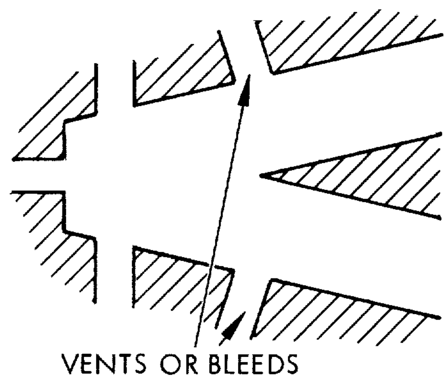
Load sensitivity has been a major problem in the design of wall attachment devices, since it is impractical to design interconnecting impedances for each separate case. To overcome this, most wall attachment elements are vented or bled off to a suitable sink, so that over an appreciable operating range, each element is automatically matched to its applied load. This approach, although inefficient in terms of required input fluid power, is quite adequate in many circuit applications where total fluid power is not critical. Load sensitivity in a wall attachment device may be decreased by one of the methods shown in Figure 8-91.

The fan-in capability of wall attachment devices is limited by the configuration; i.e., there is a practical limit to the number of control input ports which can be directed into the interaction region. A fan-in of 4 is state of the art and potentially, this should increase to about 8. Fan-out is defined as the number of similar elements which can be controlled from the output of a device operating at a common power nozzle pressure. Although fan-outs of 32 have been reported, practical fan-out capability is in the range of 4 to 6.

8.5.4.2 Beam Deflection Amplifier - Most of the design parameters indicated for the wall attachment amplifier also apply to the beam deflection amplifier. The primary difference is that the side walls in the interaction region of the beam deflection amplifier are removed to prevent wall attachment as shown in Figure 8-92. The shape and dimensions of the cutout areas have considerable influence on the performance of the amplifier. Any fluid not collected in the outputs must be vented properly or this fluid can be reflected from the wall of the cutout areas back toward the power jet to produce a feedback effect which could result in unstable operation, oscillation, and reduced gain.

In a typical vented beam deflection amplifier without a center dump, the output apertures are located about 10 power nozzle widths downstream and are about 1.5 power nozzle widths wide. The present theoretical maximum pressure gain of a beam deflection amplifier is about 20, presuming that all of the control energy is converted into momentum flux and that the power jet is at near zero position. In most designs, pressure gain is usually sacrificed in favor of reduced pressure noise. Pressure gains greater than 100 have been achieved experimentally in some of the newer beam deflection amplifiers. However, these designs require additional vents and walls close to the power jet so that pressure forces may be used to assist in the deflection of the power jet. Although pressure gain is usually the parameter of general interest, it should be understood that maximum pressure gain is achieved at the expense of flow gain, power gain, pressure recovery, and linearity so that a useful amplifier must be a compromise among all these parameters.

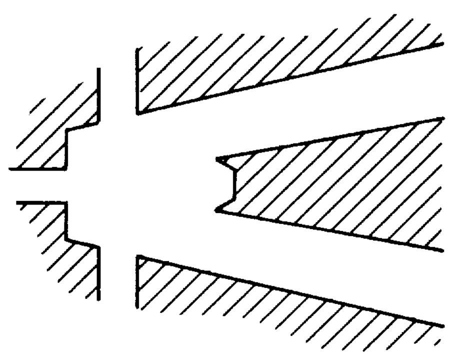
1.



VENTED OUTPUTS

VENTS OR BLEEDS IN THE OUTPUT CHANNELS ISOLATE THE INTERACTION REGION FROM DOWNSTREAM CONDITIONS.

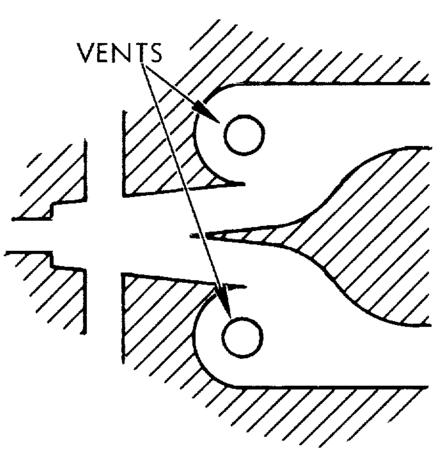
2.



CUSPED SPLITTER

THE CUSP IN THE SPLITTER GENERATES A LATCHING VORTEX ON THE PASSIVE OUTPUT SIDE OF THE POWER JET; CONSEQUENTLY, THE PRESSURE, FLOW, AND POWER RECOVERY OF THE DEVICE ARE CONSIDERABLY INCREASED. IN ADDITION, THE ACTIVE AND PASSIVE OUTPUT PORTS ARE EFFECTIVELY DECOUPLED.

3.



LATCHED VORTEX VENT

THIS VENT CONFIGURATION ALLOWS IMPEDANCE MATCHING OVER A WIDE RANGE OF LOAD CONDITIONS, FROM ZERO LOAD UP TO AND INCLUDING REVERSE FLOW INTO THE AMPLIFIER. COMPRESSION PULSES PROPAGATED BACK INTO THE AMPLIFIER INTERACTION REGION ARE ALSO ATTENUATED.

Figure 8-91. Methods of Reducing Load Sensitivity

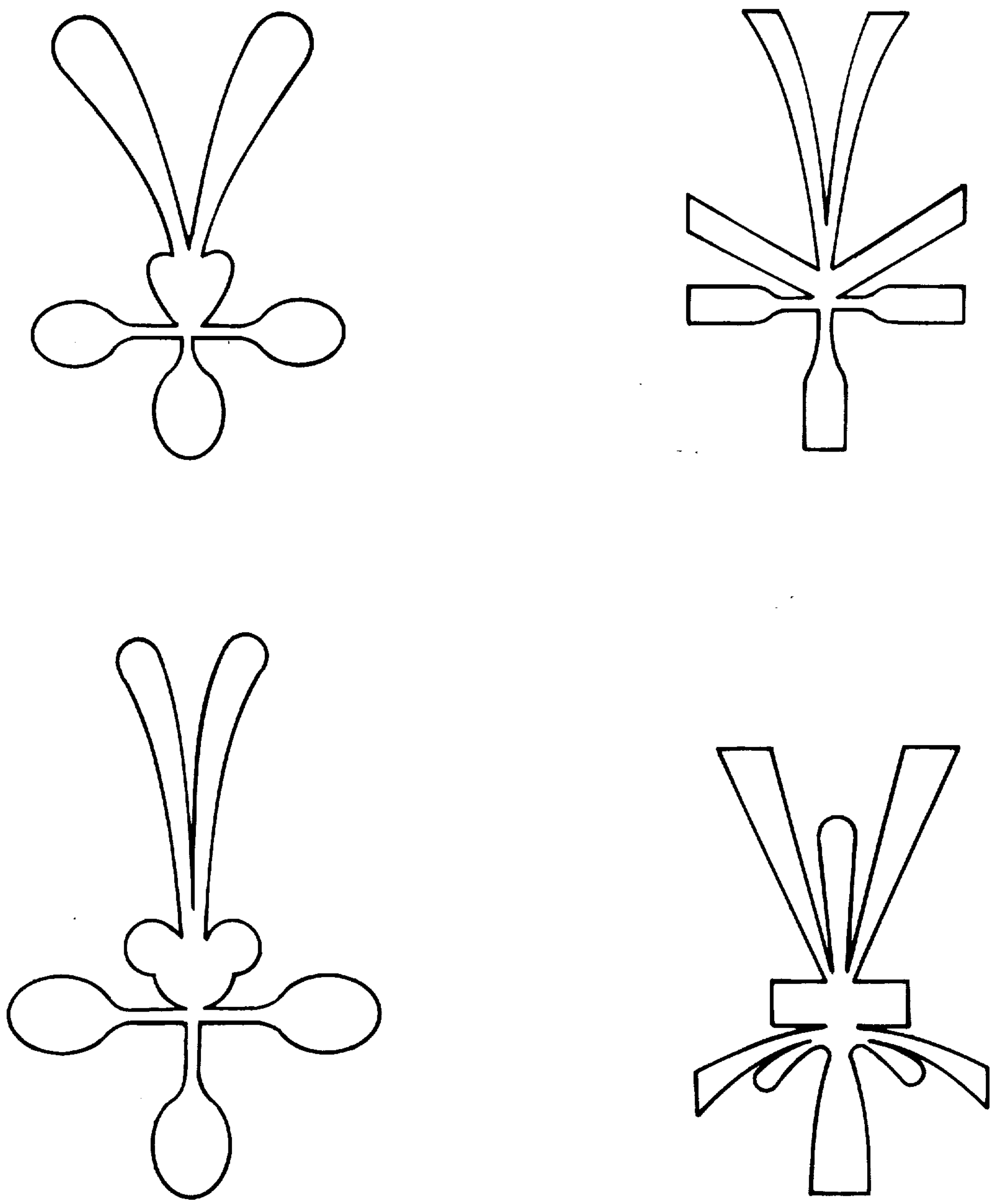


Figure 8-92. Proportional Amplifier - Interaction Region Shapes

Design information for beam deflection amplifiers may be found in References 31, 32, and 37 through 42.

8.5.4.3 Vortex Amplifiers - The nonvented vortex amplifier is the most useful vortex amplifier configuration. This amplifier can be optimized for maximum turn down by utilizing relatively small control port areas and chamber to outlet hole diameter ratios of less than 8, however, a bistable hysteretic device will result. Nonvented designs for throttling applications are nonhysteretic with minimum noise in the high gain region. To accomplish this:

1. Vortex chamber to outlet hole diameter ratio should be between 8 and 12.

2. Outlet hole to control port area ratio should be about 8.

3. Chamber length should be greater than one-half the exit hole diameter.

The turndown ratio of the nonvented amplifier is also affected significantly by the size of the control port; i.e., turndown ratio decreases as the control ports are made larger since the control velocity and consequently the momentum are decreased. The control port area and thus the optimum turndown of a particular nonvented vortex amplifier configuration depends to a great extent on the available control pressure, so that the control to supply pressure ratio at turndown must also be considered in a practical amplifier design.

The vented vortex amplifier (Figure 8-30) is usually used as a pressure amplifier. In this configuration the diameters of the vortex chamber outlet hole and the receiver tube are about the same and the receiver is usually located approximately 1 tube radius axially downstream of the chamber outlet. The gain and efficiency of the receiver output can be controlled by changing the tube diameter and the axial distance between the receiver and the vortex chamber outlet. Reducing the diameter or increasing the axial distance of the receiver will decrease the power efficiency but improve the power gain of the output. Most of the design parameters utilized for the nonvented vortex amplifier also apply to the vented vortex amplifier.

Design information for vortex amplifiers may be found in References 26, 32 and 59 through 64.

8.5.4.4 Resistors - By definition, a fluidic resistor produces a pressure drop as a function of the mass flow through it; i.e., in comparison to an electrical resistor pressure is analogous to voltage and mass flow is analogous to current. Fluid resistance may be either incremental or the average value. Incremental fluid resistance is the slope of the pressure drop versus flow curve at a specific point; i.e., $R = d(\Delta P)/d\dot{W}$. The incremental resistance is used for relatively small dynamic range around a specific operating point, and applies particularly to an orifice, which has a parabolic pressure flow characteristic. The average value of fluid resistance (also steady state or operating point resistance), is the slope of the line from the origin to the operating point on the pressure flow curve; i.e., $R = \Delta P/\dot{W}$. This resistance value is used to calculate bias flows and pressure.

Simple orifices are often used as resistors because of the ease of construction. When used with low pressure gases or incompressible fluids, their pressure flow characteristics follow the square law relationship and are therefore nonlinear. As illustrated in Figure 8-93, the expressions for orifice resistance are as follows:

Incremental Resistance:

$$R = \frac{d\ (\Delta P)}{d\dot{W}} = \frac{1}{C_d A}\left(\frac{2\ R_g\ T\Delta P}{gP}\right)^{1/2} \quad \frac{\text{sec}}{\text{in}^2}$$

Average Value Resistance:

$$R = \frac{\Delta P}{\dot{W}} = \frac{1}{2C_d A}\left(\frac{2\ R_g\ T\Delta P}{gP}\right)^{1/2} \quad \frac{\text{sec}}{\text{in}^2}$$

The above expressions are accurate for incompressible fluids and will provide adequate accuracy for compressible fluids (3 percent maximum error) if ΔP is limited to about one-half the value for P and if the value used for P is the absolute pressure downstream of the orifice.

Laminar resistors which are fabricated from metal or glass capillaries and porous plugs are essentially linear. The expression for laminar resistance is as follows:

$$R = \frac{32\ \mu\ell\ R_g T}{AD^2 P}$$

where D is the hydraulic diameter,

$$D = \frac{4A}{K_w}$$

and where K_w is the wetted perimeter.

The average absolute pressure should be used for P in the above equation and ΔP should be somewhat less than P.

With gases the actual characteristic for laminar flow is nonlinear because the average gas density also increases as the ΔP increases. Experimental results have shown that to obtain linear resistance the length of the resistor should be about 10 percent longer than indicated by the laminar flow resistance equation.

See Reference 43 for derivations of the resistance equations.

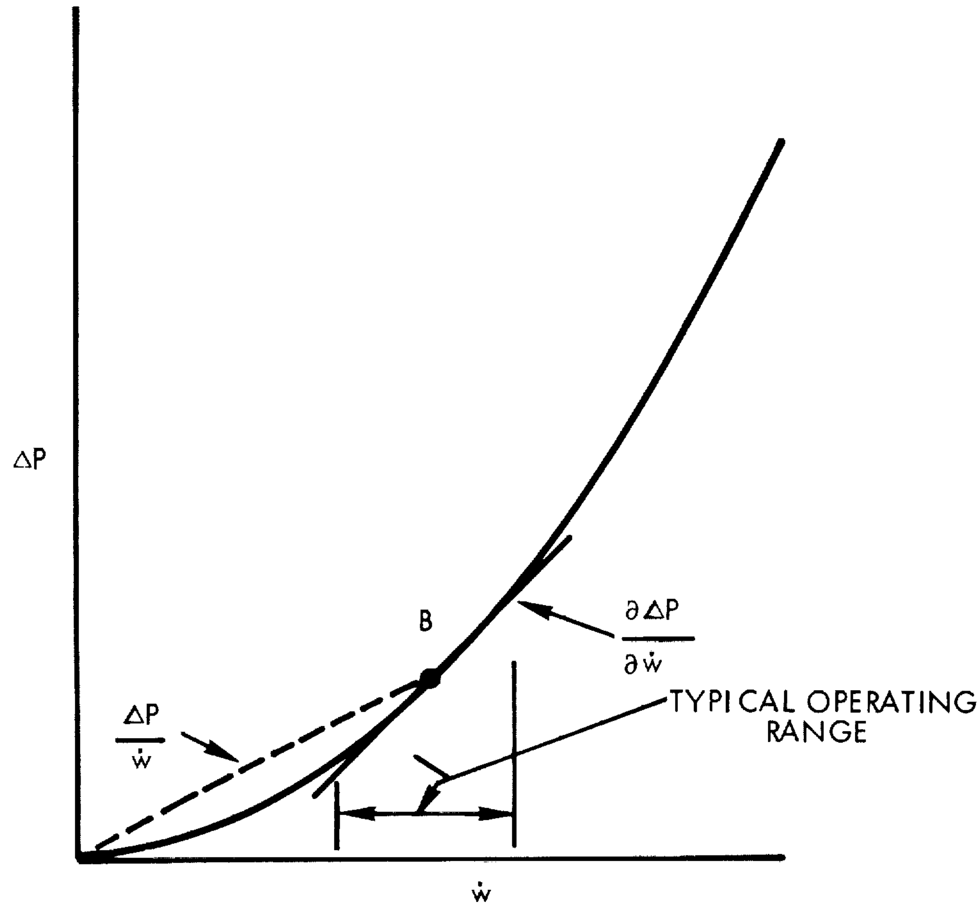


Figure 8-93. Pressure-Flow Characteristic of an Orifice

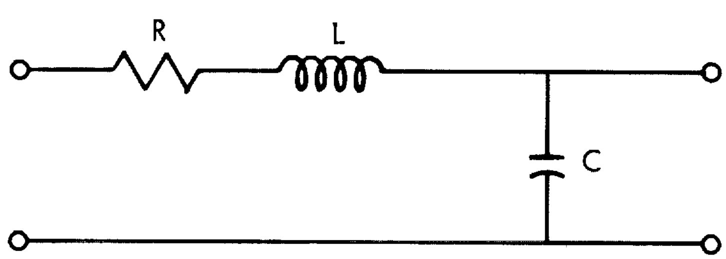


Figure 8-94. Lumped Parameter Model of Line

8.5.4.5 Capacitors - In fluidic circuits which use gas as the operating medium, the gas compressibility results in energy storage analogous to that of a capacitor in electronic circuitry. Hence, the fluidic capacitor is simply a volume for gas storage and can be used in conjunction with resistors to form first order lags with single time constants. Since liquids are essentially incompressible, much larger volumes are required to produce significant capacitance, and an accumulator or other moving parts device is generally used to provide the required energy storage in a smaller space. It is important to note that there is a capacitance associated with every element of volume in a fluidic circuit. The discussion below is concerned only with capacitance-associated gases since they are by far the most common fluidic operating media.

The capacitor in fluidics provides the function of a shunt-to-ground capacitance; the series or coupling capacitor has no analog in fluidic circuitry. A simplified analysis for determining the expression for calculating capacitance assumes adiabatic flow in a fixed volume (see Reference 43) and uses the energy equation to obtain

$$C = \frac{V}{kR_g T} \ \mathrm{in}^2$$

This expression for capacitance assumes no heat transfer, i.e., an adiabatic process which is approached for rapid pressure changes within the capacitance volume. Practical experience with air (room temperature) in fluidic circuits has shown that a value of 1.2 in place of k is the best compromise.

8.5.4.6 Inductors - The fluid in fluidic passageways has inertial properties or inertance which can result in significant dynamic characteristics. The inertial effects, which are present for both compressible and incompressible fluids, result in characteristics similar to inductance in electrical circuits. Considering a line of length ℓ and cross sectional area A, Newton's second law is used to obtain

$$L = \frac{\ell}{gA} \ \frac{\mathrm{sec}^2}{\mathrm{in}^2}$$

Thus the inductance, L, of a line is directly proportional to its length and inversely proportional to the cross sectional flow area. In practice, fluidic inductance without corresponding resistance is impossible to obtain. Laminar or linear resistors have inductive properties which must be considered in high response circuitry (see Reference 43).

8.5.4.7 Lines - The lines which interconnect fluidic elements usually have more dynamic effect on the circuit than the response of the individual elements (Reference 44). The line has both capacitive and inductive reactance as illustrated in the simple lumped-parameter model shown in Figure 8-94. For a long line a distributed parameter analysis, which is beyond the scope of this discussion, must be used (see References 45 and 46). A line is defined as short if its length is small (e.g., 10 percent) compared to the wavelength of the maximum frequency of interest. At 100 cps the wavelength is 130 inches (propagation velocity 13,000 in/sec) and thus the characteristics of a 13-inch line can be approximated with a lumped parameter model as shown in Figure 8-94.

A simplified technique for the interconnection of digital fluidic amplifiers which should be considered if it becomes necessary to reduce signal attenuation in the interconnecting lines between fluidic circuit elements is discussed in Reference 47.

8.5.5 Control Circuit Design

It is a well recognized fact that interconnecting fluidic devices into circuits and systems is a problem in the field of fluidics. It is very important to examine these difficulties carefully. Many of them have been faced to a certain degree by those working in the field of mechanics, electronics, and hydraulics. Nonlinearity is one such difficulty. It is apparent that transistors, mechanical linkages, and servovalves are nonlinear. A second difficulty concerns continuity. Both electric and hydraulic circuits must satisfy certain limited continuity principles. Kirchoff's law is a statement of continuity for electric circuits. A third difficulty results from the large number of relevant variables. Electric circuit and hydraulic system performance are affected by the variation of numerous parameters including temperature, aging, and bulk modulus. Even considering these difficulties, many electronic and hydraulic systems have been produced and are operating satisfactorily.

Therefore, it is apparent that a person working in fluidics has something to learn from the fields of mechanics, electronics, and hydraulics. He must adapt his thinking to take advantage of the analogous system design methods already developed in those fields. In other words, a thorough understanding of fluidic system operation is difficult and will remain so for many years. Approximate methods based on those used in other fields yield good results in the great majority of cases and provide tremendous insight into the operation of the system. As a result, these techniques will accelerate the advance of fluidics technology by making it possible for a circuit design engineer to use fluidic devices now, without an elaborate education in fluid mechanics.

In the design of any system of interconnected components, it is necessary to take into account the effect of one component upon the other--that is, of cross-coupling. This statement is true whether the components are electronic, mechanical, hydraulic, acoustic, or fluidic.

The most practical systematic procedure used in control system design is the so-called black-box method. This technique requires that each component be isolated from all other components in the system and then be subjected to a few simple tests under typical operating conditions. These processes are normally performed by the manufacturer before he ships a component to a user. For example, the vacuum tube manufacturer supplies a set of characteristic curves and dynamic parameters for each tube he markets, and the servovalve manufacturer supplies output pressure-flow characteristics. By using the same proven approach, all the mathematical tools now used in electronics and hydraulics can be applied to fluidic circuit analysis and design. This systems approach is defined in detail in References 8 and 48.

8.5.6 Formal Analysis

This section briefly outlines some analytical techniques and tools that could be used to help synthesize and design fluidic systems from a component level and to reduce the time, cost, and uncertainty involved with present repetitive cut-and-try methods. Analysis should be based on component performance data (characteristic curves) which are either made available by the component manufacturer or derived from suitable laboratory testing which is coordinated with the analytical effort. Implementation of analytical techniques will support the system designer in specifying, monitoring, and verifying fluidic component operation in both linear and/or nonlinear system applications. In addition, these techniques should be useful in the specification of the type of testing required for proper component checkout, which will help to ensure successful system design.

8.5.6.1 Analytical Techniques - In order to perform a useful analysis of fluidic systems, it will be necessary to model the operation of the components and associated connecting passageways involved from a dynamic as well as a static viewpoint. There are several ways that the dynamic and static analysis of fluidic systems can be approached. Two possible ways are:

1. Fluid dynamic analysis of the detailed complex flow phenomena involved.

2. Fluid circuit analysis analogous to the approach used for electronic circuit design.

The fluid dynamic analysis approach has yielded very little practical information for fluidic system designers to date due to the nonlinearities involved in the governing partial-differential fluid flow equations (Navier-Stokes). This is true both at the component and systems levels. Thus, the first approach is not recommended as it does not appear to be applicable to overall fluidic system design at the present time.

A logical area for fluidic system modeling lines in the second approach; i.e., the application of fluid circuit theory as outlined in Reference 7 and further discussed in Reference 49 in connection with a dynamic analysis design philosophy for fluidic systems. Each of these references points out the logical adaptation of equivalent electrical circuit theory utilizing a mix of lumped and distributed parameters to perform fluidic system modeling. Circuit theory is applicable to the interconnecting lines between circuit elements and is covered in detail in Reference 32. It should also be applicable to fluidic components themselves in a manner similar to that used in Reference 50 in defining small signal dynamics of various proportional amplifiers by means of derived equivalent circuits which is an adaptation of electronic design techniques.

In areas where application of circuit theory becomes untractable, it will be necessary to use the black box technique (see Section 8.5.5), based on extensive fluidic component testing (both static and dynamic), to establish the required analytical transfer functions for the fluidic device in question.

Binary logic design should be based on standard techniques, such as Boolean algebra, which have been developed and used in the design of digital computers. These techniques will be helpful in optimizing the selection and combination of bistable fluidic components such as flip-flops, OR-NOR, and AND-NAND gates into such digital devices as adders, counters, timers, multivibrators, and shift registers, to be used for either sensing, logic or control functions.

8.5.6.2 Analytical Tools - The analytical tools needed to perform fluidic circuit analysis fall into two categories:

1. Analytical Techniques - Large-signal nonlinear problems using graphical techniques and small-signal problems using linearizing approximations.

2. Computer Aided Design (CAD) Techniques - Based on programmed solutions generated on analog, digital, or hybrid computers, used to solve either small or large-signal linear or nonlinear problems.

In general, the application of purely analytical techniques to the design of fluidic systems will be limited to relatively simple circuits. Techniques for performing analyses for both small signals based on equivalent linear circuits and large signals based on graphical analysis are covered in Reference 50. The techniques outlined in detail in this reference are similar to the standard procedures used for both single and multiple stage electronic circuit design. The only new facet that has been added is the generation of equivalent circuits which include the time delays association with signal propagation.

The application of computer analysis is recommended for the design of relatively large, complex, fluidic systems to achieve a more rapid turn-around time than presently possible. This approach should also minimize the costs associated with the system design, development, and test cycle.

There are two digital programs, ECAP and SCEPTRE, which are presently being used to aid electronic circuit designers in the design and development of complex electronic circuits. Use of these programs helps minimize the costs associated with the breadboarding and testing of actual hardware prior to finalizing a design. Since both of these programs are circuit analysis oriented, they can also be gainfully used for computer analysis of complex fluidic systems utilizing fluidic component performance data to characterize and model the equivalent networks.

ECAP (Reference 51) is basically oriented to handle small signal or linear circuits. To use the program, an equivalent linear circuit is first established in which any representation of such components as diodes and transistors can be used, provided it can be modeled with conventional linear passive circuit elements, voltage and current sources, and current sensing switches. The matrix approach is fundamental (solution is not dependent on a transfer function approach) and information on basic network branches (circuit topology) are key entries to the computer. The input to the program is user-oriented; i.e., no translational language is needed. ECAP can perform DC, AC, and transient analysis and has options for sensitivity, standard deviation, and worst-case analysis. The latter options are useful in establishing component tolerance criteria which are compatible with overall system performance specifications. Reference 50 provides equivalent circuits for fluidic components which can be used in ECAP to perform AC analysis (provide system frequency response) with suitable modifications to include fluidic component and circuit connection time delays.

The SCEPTRE program (see Reference 53) was written to allow the designer to perform both DC and transient analysis of large nonlinear electronic networks. The input format of this program again basically describes the topology of the circuit and the discrete circuit elements. However, unlike ECAP, these circuit elements may be nonlinear and/or linear. The input format for nonlinearities can be either tables or equations. In addition, active models can be built up from passive elements and stored in a library and recalled for use as needed. Thus, SCEPTRE should facilitate fluidic circuit modeling and analysis for large signal cases provided that the fluidic time delays are monostable or bistable switching devices used either as relays or to implement logic operations. Modeling involving component cascading would be simplified through the use of the stored model feature. Impedance matching and/or stage isolation in the case of cascaded analog and digital components would also be facilitated through the use of SCEPTRE.

On-line computers can be used to help optimize the design and checkout of both synchronous and nonsynchronous digital logic circuitry which involve fluidic switching hardware. This analytical approach would be especially useful to ensure the acceptable operation of switching networks operating at relatively high speeds.

Timing problems can arise in this case due to inherent fluidic system time delays and the effect of signal noise modification of the signal pulse width which could cause a loss of signal. Examples of the problems involved and proposed solutions are given in Reference 32.

8.6 PROPULSION APPLICATION STUDIES

8.6.1 Preliminary Considerations

Fluidics technology has not progressed to the point where completely fluidic (no moving part) controls are practical in liquid propulsion systems. Fluidic applications in this area must then be considered in two phases which are defined as hybrid and completely fluidic systems. Hybrid applications are estimated to be about 2 to 5 years away, and completely fluidic applications are 5 to 10 years away.

In both phases, the control functions to be considered include:

1. Pressure and flow regulation of pressurants and propellants

2. Instrumentation to sense system parameters

3. Transducers to interface with other control disciplines

4. Specific control functions - i.e., monopropellant and bipropellant feed systems, mixture ratio control, thrust vector control, and attitude control.

For the long term, the major technology improvements required to provide completely fluidic control functions are:

1. High gain proportional amplifiers - both liquid and gas operated. Present amplifiers are limited to pressure gains of from 5 to 20, however, gains of 50 to 150 are required and appear feasible.

2. Nonvented systems or methods of minimizing overboard vent requirements - venting or constant pressure dump sources are presently necessary to ensure predictable and optimum fluidic device performance. Absolute pressure references also require venting.

3. Power sources - recirculating power supplies need to be considered and on a systems basis the use of bleed gas, propellant boiloff gases, etc.

The use of hybrid controls should be based on tradeoff studies with existing systems which include size, weight, and reliability as well as performance. Electrical to fluid transducers are needed which have lower power drains than present devices and preferably without mechanical interfaces. To perform power functions, consideration also has to be given to specifically designed mechanical interfaces with primary emphasis on the elimination of sliding mechanical parts.

Control system shutoffs will present a major problem in both the short and long range applications. The usual electromechanical and explosive type shutoffs can be considered initially for the hybrid controls. The design of the shutoff valve function should be based on simple flexures, such as diaphragms and bellows, including several of the valve concepts studied under this program. These include the electroseal and the electromagnetic capillary valves. At present, a completely fluidic shutoff valve (without venting) is not available.

To aid in the planning of specific application studies, an effort was made to categorize the possible ways fluidics can be applied to propulsion controls. Six major categories were selected and defined (Table 8-7) and these were subsequently broken down into subcategories. The range of possible applications is quite broad and a complete comprehensive study is not within the scope of this task. Consequently, specific areas of detailed investigations were defined under each subcategory. These areas were then reviewed relative to the objectives of this task, and ratings were assigned in the order of importance with 1 being the most important (Table 8-8).

8.6.2 Generalized Application Criteria

The most prominent potential improvements fluidic components offer are in the size, weight, and reliability of systems where it is advantageous to use a single fluid medium for all control functions and the need to translate information from one medium to another is eliminated. In evaluating systems, the ease or difficulty with which a mechanization concept meets a particular requirement is reflected in those parameters (size, weight, and reliability) which can be effectively compared. For example, a fluidic vortex valve can be designed to operate in a 2000°F environment without cooling. An electrically operated valve can also be made to operate in the same 2000°F environment, but only with additional cooling devices which add to the size and weight and reduce the reliability of the valve. This means that stability, response, and ambient temperature capability are not direct items of comparison but are basic requirements for all components.

While a number of factors are involved in the evaluation, it is ultimately the cost or cost effectiveness of the proposed item which determines its acceptance or rejection. Thus, reliability, weight, performance, etc., are ultimately expressed in the cost necessary to employ the system and obtain the desired return. The cost of a program may be divided into conceptual development (acquisition), and maintenance (operational) phases with the following primary contributing factors:

- System Weight
- System Packaging
- Reliability
- System Performance
  - Accuracy
  - Repeatability
  - Power Consumption

These criteria provide an effective means of evaluating subsystems for propulsion system use. In the case of fluidics, a decision on its applicability to a particular use cannot be limited to a "yes" or "no", but must also consider the particular hybrid use of a few elements in conjunction with electromechanical, pneumomechanical, electrohydraulic, and other currently available components. The extent to which fluidics can be used is heavily dependent upon the mission length and duty cycle (on time/total mission time).

Table 8-7. Propulsion Applications of Fluidics

I. Fluidic Propellant and Pressurant Control Control components utilizing fluidic principles exclusively, i.e. no moving mechanical parts.	I-1 Pressure Control I-2 Flow Control I-3 Mixture Ratio Control I-4 SITVC
II. Instrumentation Fluidic control components required to sense system parameters and interface with other controls, including simple moving part concepts.	II-1 Sensors II-2 Electrical Interfaces II-3 Mechanical Interfaces II-4 Fluid Interfaces
III. Fluidic Techniques for Component and System Improvement The use of fluidic principles to improve the function of conventional components and systems.	III-1 Vortex Generation III-2 Jet Interaction III-3 Surface Interaction III-4 Combined Effects
IV. Fluidically Controlled Valves The use of fluidic controllers with specifically designed mechanical power stages.	IV-1 Shutoffs IV-2 Flow Control IV-3 Pressure Control
V. Fluidic Computation The use of fluidic computation techniques to perform propulsion related control functions.	V-1 Digital V-2 Analog V-3 Combined Techniques
VI. Major Applications Representative fluidic and hybrid applications wherein fluidic technology can make a significant contribution.	VI-1 Medium Thrust Propulsion VI-2 Attitude Control and Station Keeping VI-3 High Thrust Propulsion VI-4 Astronaut Mobility

Table 8-8. Relative Importance of Specific Application Areas

I. FLUIDIC PROPELLANT AND PRESSURANT CONTROL

I-1 Pressure Control

- Liquid Pressure Regulator (1)
- Liquid Pressure Relief (4)
- Gas Pressure Regulator (1)
- Gas Pressure Relief (3)
- Pressure Controllers (1)
- Mixed Media Pressure Regulator (1)

I-2 Flow Control

- Liquid Flow Regulator (1)
- Gas Flow Regulator (1)
- Mixed Media Flow Regulator (1)

I-3 Mixture Ratio Control

- Specific Application Without Moving Parts (2)

I-4 SITVC

- LITVC (2)
- Gas Injection (3)
- G.G. Controlled (3)
- Bleed System (4)

II. INSTRUMENTATION

II-1 Sensors

- Flow (4)
- Pressure (4)
- Temperature (4)
- Position (3)
- Speed (4)

Table 8-8. Relative Importance of Specific Application Areas (Continued)

II-2 Electrical Interfaces

- Electrical to Fluidic (4)
- Fluidic to Electrical (4)

II-3 Mechanical Interfaces (3)

II-4 Fluid Interfaces (2)

III. FLUIDIC TECHNIQUES FOR COMPONENT AND SYSTEM IMPROVEMENT

III-1 Vortex Generation

- Flow Limiting (2)
- Flow Separation (2)
- Signal Isolation (3)

III-2 Jet Interaction

- Flow Biasing (3)

III-3 Surface Interaction

- Geometric Biasing (3)
- Duct Shaping (3)
- Vane Control (2)

III-4 Combined Effects (3)

IV. FLUIDICALLY CONTROLLED VALVES

IV-1 Shutoffs

- Propellant Controlled - Actuated (1)
- Pressurant Controlled - Actuated (1)
- Pressurant Controlled - Propellant Actuated (1)

Table 8-8. Relative Importance of Specific Application Areas (Continued)

IV-2 Flow Control

- Propellant Controlled - Actuated (1)
- Pressurant Controlled - Actuated (1)
- Pressurant Controlled - Propellant Actuated (1)

IV-3 Pressure Control

- Propellant Controlled - Actuated (1)
- Pressurant Controlled - Actuated (1)
- Pressurant Controlled - Propellant Actuated (1)

V. FLUIDIC COMPUTATION

V-1 Digital

- Sequencing Functions (3)
- Timers (3)
- Digital Controllers (4)

V-2 Analog

- Analog Controllers (3)
- A.C. Techniques (4)

V-3 Combined Techniques

- Specific Examples (4)

VI. MAJOR APPLICATIONS

VI-1 Medium Thrust Propulsion (50 to 1000 pound thrust range)

- Monopropellant Feed Systems (1)
- Bipropellant Feed Systems (1)
- Propellant Management (3)
- Ground Support Equipment (4)
- Monopropellant Gas Generation Systems (3)

Table 8-8. Relative Importance of Specific Application Areas (Continued)

VI-2 Attitude Control and Station Keeping

- Single Source Attitude Control (3)
- Single Source Station Keeping (4)
- Proportional Attitude Control (2)
- Combined Attitude Control Station Keeping (4)

VI-3 High Thrust Propulsion

- Liquid Chemical Rockets (1)
- Nuclear Rockets (4)
- Solid Rockets (4)
- Hybrid Rockets (3)

VI-4 Astronaut Mobility

- Individual Space Propulsion Units (3)
- Space Transfer Vehicles (3)
- Ground Effect Machines (3)

To illustrate these criteria, both a conventional and a fluidic monopropellant hydrazine feed system (Figure 8-95) were devised to perform identical functions. The fluidic system was purposely made a hybrid for the sake of simplicity. The hydrazine load and flow rate, nitrogen flow rate to the propellant tank, and the regulator and propellant tank weights are identical in both systems so they were not considered further. In the case of the conventional system the weight of the solenoid valve and driver was estimated to be 3 pounds and the electrical power required to operate the solenoid valve was based on a battery capacity of 40 watt-hr/lb. For the fluidic system the weight of the fluidic elements was estimated to be 0.5 pound and the additional nitrogen and storage tank weight required to operate the fluidic vortex throttle was accounted for as a function of mission life. The fluidic system was not penalized for the vortex valve vent flow, because in this particular application the vented nitrogen was regulated down for use in another fluidic control system. On the basis of these assumptions and system parameters, the weight ratio of the conventional system and the fluidic system as a function of duty cycle (Ø) and mission life (T) is given in equation (1).

$$\frac{W_c}{W_f} = \frac{W_{sv} + W_b}{W_f + W_{cg}} \qquad (1)$$

where

W_c = total weight of conventional feed system, lb_f

W_f = total weight of fluidic feed system, lb_f

W_{sv} = weight of solenoid valve and driver, lb_f

W_b = prorated battery weight obtained from equation (2), lb_f

W_f = weight of fluidic components, lb_f

W_{cg} = weight of fluidic control gas, including prorated tank weight, obtained from equation (3), lb_f

$$W_b = \frac{P_s \, \emptyset \, T}{60 \, N_b} \qquad (2)$$

where

P_s = solenoid power requirement, watts

$\emptyset$ = duty cycle (on time/T), dimensionless

T = mission life or mission duration, min

N_b = battery energy density, watt-hr/lb_f

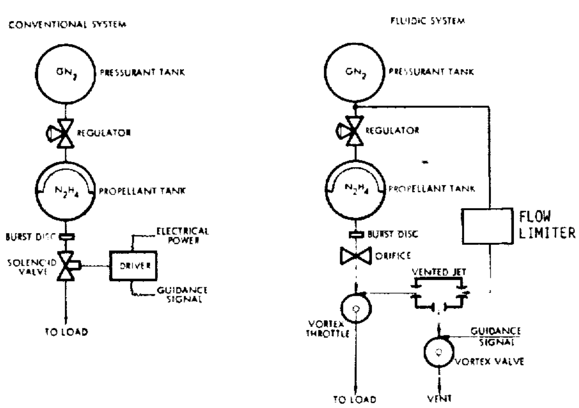


Figure 8-95. Monopropellant Hydrazine Feed Systems

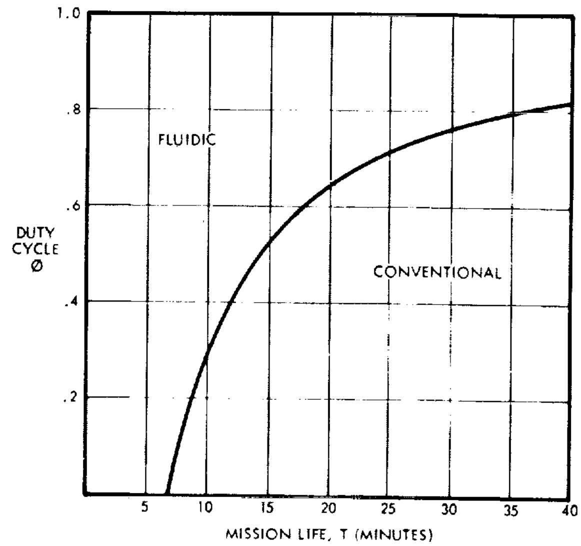


Figure 8-96. Optimum System Weight Regimes

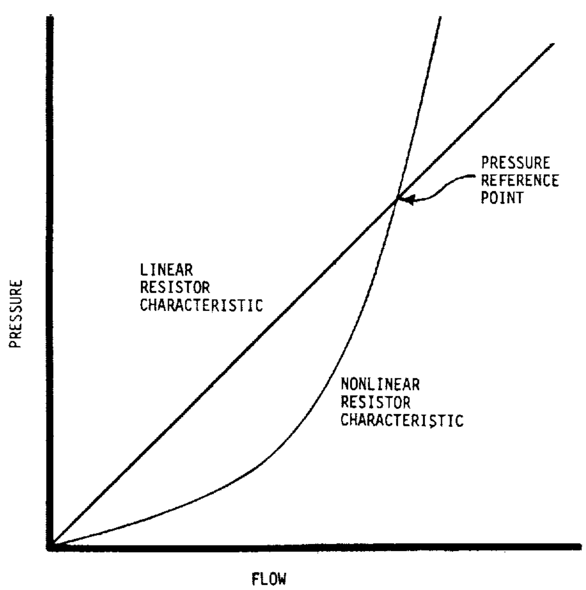


Figure 8-97. Characteristics of Linear-Nonlinear Resistor as a Pressure Reference

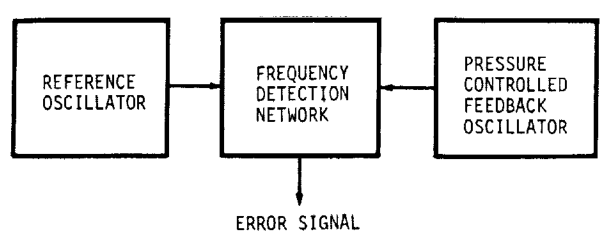


Figure 8-98. Oscillator Pressure Reference - Block Diagram

$$W_{cg} = (1 + C_t)\ \dot{w}_{cg} T\ (1 - \emptyset) \tag{3}$$

where

C_t = tank constant (tank weight/pressurant weight), dimensionless

$\dot{w}_{cg}$ = control gas flow rate, lb_f/min

Equation (1) is plotted in Figure 8-96 as a function of duty cycle and mission life for the condition where $W_c = W_f$, using the following values:

W_{sv}	=	3 lb_f	N_b	=	40 watt-hr/lb_f
W_f	=	0.5 lb_f	C_t	=	1.7
P_s	=	12 watts	$\dot{w}_{cg}$	=	0.132 lb_f/min

The curve defines where the two system weights are equal, and consequently defines the minimum system weight regimes for each system. The dividing line between the regions shown in Figure 8-96 will be flexible from system-to-system and dependent upon the cost factors previously described. System weight is the major factor in defining these regions while reliability is the deciding factor where a final selection is not clearcut. Obviously this type of analysis is only as good as the assumptions made, however, we have found it useful in evaluating the applicability of fluidic systems.

8.6.3 Fluidic Pressure References

Precise pressure signals are needed for various functions in propulsion systems. The primary uses are seen as set points for fluidic pressure regulators, reference signals for fluidic controllers, and a necessary prerequisite to accurate time delays in sequential fluidic circuits.

The difference in the characteristics of an orifice and a linear resistor can be used to obtain a pressure reference suitable for use in a fluidic control system. The more general technique is to use the difference in momentum flux of the flow rates in two parallel flow legs as the error signal by applying these flows directly to the control ports of a proportional amplifier as shown in Figure 8-97. The orifice and resistor are sized so that the control flows to the proportional amplifier are equal at the desired reference pressure.

For a constant upstream pressure, the ΔP across a laminar restrictor is directly proportional to the absolute temperature and the ΔP across an orifice is inversely proportional to the absolute temperature. Consequently, the desired reference pressure will change with variations in fluid temperature, and temperature compensation becomes an important consideration when utilizing a linear restrictor versus a nonlinear orifice as a pressure reference. Several methods have been proposed, which entail compensation of either resistor by adjustment of the resistance as a function of temperature. One scheme utilizes the differential expansion of a contoured needle in an orifice to perform the required compensation.

Fluidic oscillators (see Section 8.4.8) also offer a means of achieving precision pressure references. In a fluidic regulator, the reference oscillator frequency would represent the regulator set point (Figure 8-98). Its output is then compared with a feedback signal whose frequency represents the analog pressure output of the regulator, i.e., the output could be fed back through a pressure controlled oscillator, so as to generate a frequency signal indicative of the output. This feedback signal and the reference oscillator signal are then compared, and an error signal representing their difference is generated.

The requirements of a reference oscillator are quite stringent, in that it needs to be both pressure and temperature insensitive. However, the right course of action appears to be the optimization of a temperature insensitive oscillator through the use of the inherent characteristics of distributed parameter and lumped RC feedback ducts, then to correct for pressure sensitivity by the use of a pressure controlled oscillator and a frequency discrimination network. The turning fork oscillator (Section 8.4.8.5), although hybrid in nature, offers an extremely accurate frequency reference.

8.6.4 Fluidic Pressure Regulation

A pressure regulator is defined as a component, or valve, that controls pressure by varying flow as a function of the sensed difference between the actual and the desired value of pressure. In propulsion systems, the term pressure regulator is generally accepted as meaning any device which maintains a predetermined upstream, downstream, or differential pressure by means of a pressure reducing control element. The most common applications are to provide a constant pneumatic pressure in a liquid storage tank for direct expulsion or to maintain pump suction head requirements.

Since gas is more efficiently stored in pressure vessels at high pressure (3000 psig or greater), the pressure reducing regulator is the most common type used in spacecraft systems. Pressure reducing regulators reduce upstream pressure to a predetermined downstream pressure regardless of upstream pressure variations and can be classified as modulating or nonmodulating. A modulating pressure regulator can achieve any steady-state flow rate necessary to maintain a constant regulated pressure, and consequently is the most common. A nonmodulating regulator is simply a two-position device which is often referred to as a "bang-bang" regulator. A solenoid valve operated by a pressure switch would be an elementary nonmodulating regulator.

The temperature extremes normally encountered in spacecraft applications change regulator set points by thermal contraction or expansion. In spring loaded regulators, simple compensation is accomplished by insulating or caging the reference spring. However, it is a complex problem to accurately predict and/or accurately determine the exposure to changes in temperature, so that complex thermal compensators are the general solution. Vibration poses one of the most difficult design problems since poppets, springs, and bellows are particularly susceptible. Acceleration requirements for spacecraft vehicles also impose severe g-loads along any axis, so that compensation is necessary to accurately maintain the regulator set point.

A fluidic pressure regulator should be simpler and have few, if any, moving parts. Consequently, longer storage life, higher reliability, and greater environmental tolerance should result. Improvements in size, weight, and cost are other excellent reasons for considering their future application in spacecraft systems.

8.6.4.1 Throttling Methods - A nonvented vortex amplifier exhibits a variable and controlled impedance. The impendance is produced by a combination of the pressure-flow characteristics of orifices and the radial pressure distribution in vortex flow; the variable impedance is induced by control of the tangential velocity of the vortex field.

An optimized double exit nonvented vortex amplifier will presently give a turndown ratio of 8 for a control to supply pressure ratio (P_c/P_s) of 1.2. For gas regulation, it is impractical to use a fixed area orifice to drop the amplifier supply pressure below the storage tank pressure to obtain the necessary P_c/P_s ratio. This is the case because the pressure dropping orifice becomes sonic during tank blowdown and consequently can not be controlled by the downstream vortex amplifier even for a slight decrease of the tank pressure.

It has been shown (Reference 54) that staging of nonvented vortex amplifiers, will give no improvement in turndown, i.e., the overall turndown ratio of two series connected vortex amplifiers (Figure 8-99) will in general be less than the turndown ratios of the individual amplifiers. The primary reason for this is that it would be impossible to operate amplifier B in a fully turned down condition, since provision must be made for the control flow from amplifier A when it is in a turned down condition.

Another method of cascading vortex elements is to use a vented vortex amplifier as a pilot which feeds the control and supply ports of a nonvented vortex amplifier (Figure 8-100). The differential pressure range between the two pickoff exits of the vented amplifier changes much more rapidly than the control pressure, and the central pickoff sees up to 98 percent of the supply pressure with no control flow and almost zero pressure when the pilot amplifier is turned down. This arrangement should give an overall turndown ratio of from 10 to 20 percent better than for that of a single nonvented vortex amplifier.

The vortex devices discussed previously are characteristic of methods of throttling flow without overboard bleeds. Proportional and bistable amplifiers can also be used as throttling devices, however, these devices must be operated with two output legs, one tied to the regulated load and the other dumped to atmosphere. Consequently, the throttle not only must live with the relatively low power recovery of the amplifiers (about 50 percent), but must also dump flow continuously in the regulation mode. For a blowdown source and a variable load, these power losses may preclude acceptable regulation efficiencies.

8.6.4.2 Pressure Reference Methods - The deviation of the regulated pressure from the desired value or set point, must be sensed in a high gain circuit so as to provide a feedback signal which can be used to control the throttling element. A pressure reference may require separate devices for its function alone, or the reference can sometimes be an intrinsic part of the feedback circuit.

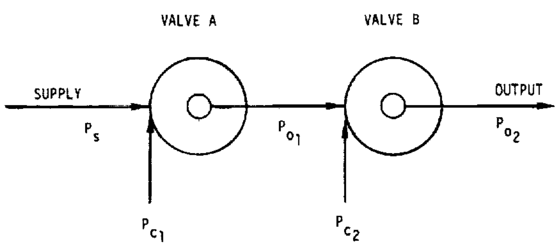


Figure 8-99. Series Connected Non-Vented Vortex Amplifiers

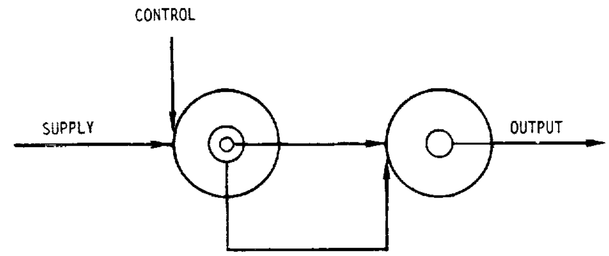


Figure 8-100. Vented and Nonvented Vortex Amplifier Cascade

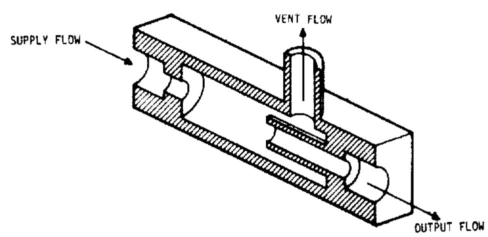


Figure 8-101. Vented Jet Amplifier Configuration

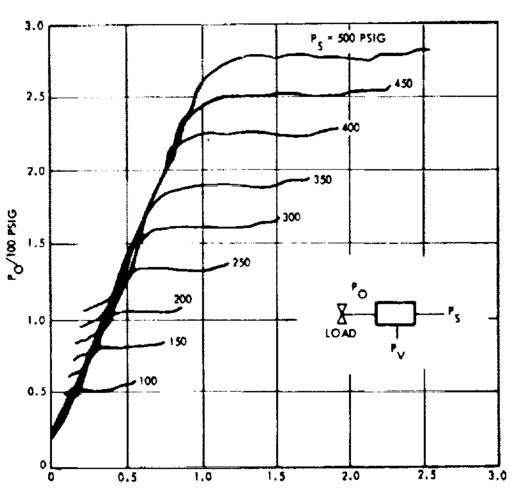


Figure 8-102. Vented Jet - Typical Performance

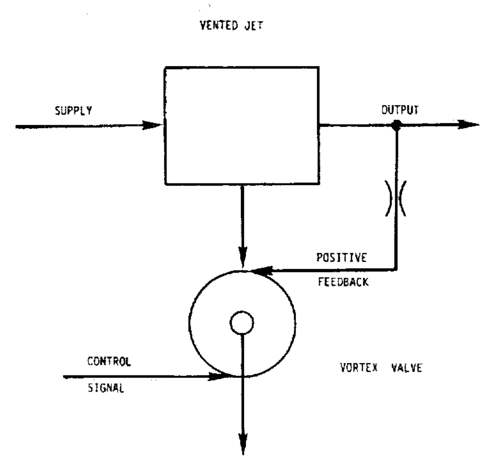


Figure 8-103. Vented Jet - Single Stage Feedback Amplifier

The most widely used pneumatic pressure reference, which was discussed previously, utilizes the difference in the characteristics of a nonlinear and a linear resistor (Figure 8-97). When the regulated pressure is as desired, the control inputs to the amplifier will be identical and the differential output pressure, ΔP_O, will be zero. If the regulated pressure becomes higher or lower than the set point, there will be a differential output from the amplifier which can be integrated and further amplified in a feedback circuit to provide the power gain necessary to adjust the throttling element.

The primary problem with state of the art pressure reference schemes is temperature sensitivity. Very little effort has been expended to date in the area of temperature compensation, and a concentrated effort should be made to come up with a temperature compensated absolute pressure reference. In particular, fluidic oscillators have been compensated (Reference 55) over a wide temperature range by using a distributed parameter feedback duct.

8.6.4.3 Feedback Methods - These are defined as the circuits that are used to generate signals which are used to control the throttling elements as a function of the deviation of the output pressure from the set pressure. Although the term regulator implies the use of feedback, the requirements of a nonmodulating regulator can be met by programming the effective area of the throttling element as a function of the tank pressure. However, the anticipated future regulator requirements for space systems point to variable load conditions which require closed-loop control.

The vented jet amplifier utilizes the properties of a freely expanding jet impinging on a receiver (Figure 8-101). By confining the jet, and controlling the vent rate of gas from the chamber, useful amplification is achieved. In this device a high pressure source is controlled by a low pressure source. By varying the geometry and spacing of the nozzle and the receiver, several gain characteristics can be obtained. Supply pressures are normally controlled by vent to supply pressure ratios, P_V/P_S, of 0.1 to 0.3, with maximum output flow and pressure recoveries on the order of 70 to 90 percent.

Typical performance of a vented jet amplifier with a fixed area load is shown in Figure 8-102. An interesting and useful property of the vented jet is shown in the figure, i.e., if the vent pressure is held at about 50 psig, the output pressure is practically independent of the supply pressure in the range from 250 to 500 psig.

The vented jet amplifier is particularly useful in controlling a vortex throttling element because of its high pressure recovery (>70 percent) when supplying a flowing load. A single-stage feedback amplifier is formed by using a nonvented vortex amplifier to control the vent pressure of the vented jet as shown in Figure 8-103. The use of positive feedback increases the output pressure recovery and reduces the control pressure required to deliver the maximum output pressure.

Stream interaction proportional amplifiers can be interconnected in analog circuits to generate feedback signals. Passive devices are used in these circuits to provide resistive, capacitive, and inductive characteristics. Analog lead-lag, lag-lead, and integration circuits have been successfully fabricated for several applications.

8.6.4.4 Vortex Regulation Concepts - The nonvented vortex amplifier is the only presently known fluidic device that is capable of throttling flow with acceptable efficiency. However, a major disadvantage is that this amplifier requires a source of control pressure higher than the supply pressure. Installation of a series orifice in the supply line to obtain the necessary P_c/P_s ratio for control is not practical, since flow turndown will occur only after the orifice becomes subsonic. The following regulator designs are presented as representative of the state of the art efforts in pressure regulation using vortex elements.

8.6.4.5 Dual Volume Regulation System - One of the simplest vortex regulation concepts would be to store part of the gas at higher pressure for control purposes (Figure 8-104). If the low pressure supply is at 2000 psig, the control pressure required for supply pressure cutoff would be about 2400 psig. Then if the feedback circuit can deliver a control pressure up to about 80 percent of the high pressure supply, the high pressure supply should be at about 3000 psig. Under these conditions, a dual exit non-vented vortex amplifier with a turndown ratio of 10, would provide a throttling range from 2000 to 200 psig. A further increase in the throttling range should be possible by using the vented vortex amplifier piloted non-vented vortex amplifier concept discussed earlier.

The necessity of having to store pressurizing gas at two different levels must be considered a disadvantage, since the trend has been for gas storage bottle pressures to increase, particularly in space applications. Theoretically, it can be shown that the weights of single compartment spherical pressure vessels and cylindrical vessels with spherical ends are independent of the storage pressure. However, storage volume decreases inversely as the initial storage pressure, and ullage is also reduced. Another problem, is the possibility of leakage disturbing the required balance between the weights of gas stored in the two volumes. One possible approach to a dual compartment pressure vessel (Reference 65), is to use a high pressure vessel installed within a low pressure vessel such that the pressure in the low pressure vessel supports the wall of the high pressure vessel.

8.6.4.6 Lag Circuit Regulator - This regulation concept (Figure 8-105) uses a conventional nonvented vortex amplifier and a double delay or lag circuit to control pressure. When the squib valve is opened, fluid flows through the fixed orifices, A_1 and A_2, and starts to charge the two volumes. Area A_2 is made larger than A_1 so that volume V_2 charges faster than V_1, which provides control pressure to the confined jet amplifier first, which in turn controls the amplifier. Initially as the pressure in V_1 is low, the vortex amplifier is almost completely open. As the pressure in V_1 increases, the vortex amplifier is completely turned down by the vented jet amplifier, so that regulated flow is supplied to the load primarily through the vortex amplifier control port. After V_1 reaches its peak, it will then decay with the storage bottle pressure. Subsequently, when the storage pressure is considerably reduced, the vortex amplifier will reopen to provide a lower pressure drop path from the supply to the load. The vent of the confined jet amplifier is controlled by the load pressure, which adjusts the output of the confined jet so as to keep the load pressure constant.

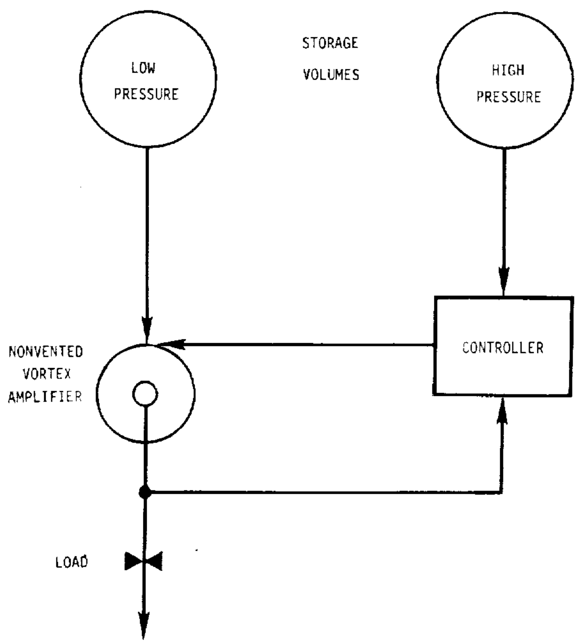


Figure 8-104. Dual Volume Regulation System

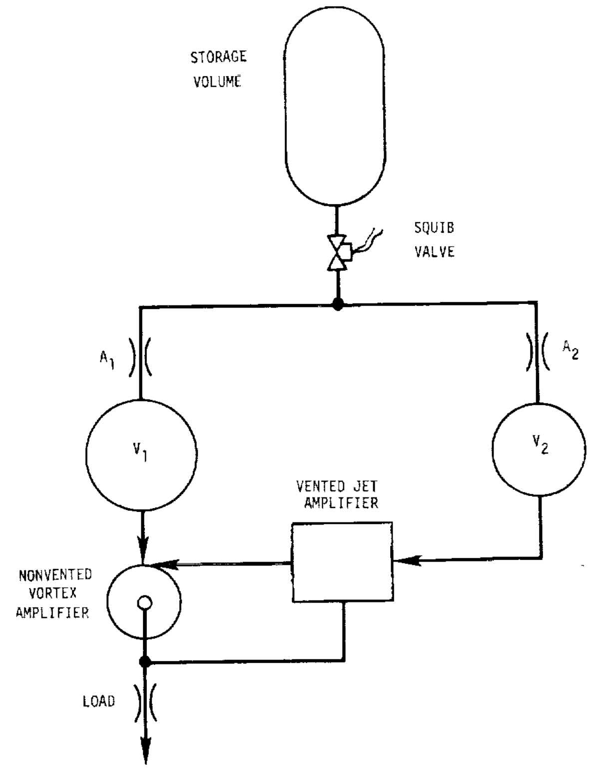


Figure 8-105. Lag Circuit Regulator

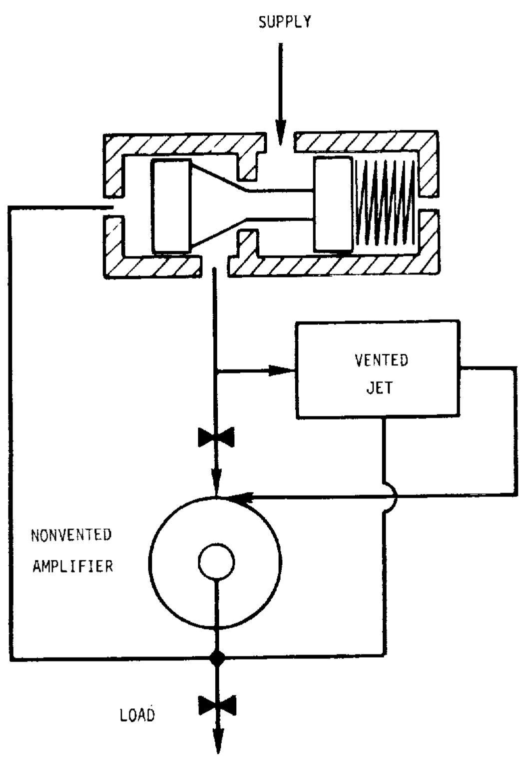


Figure 8-106. Hybrid Regulator Scheme

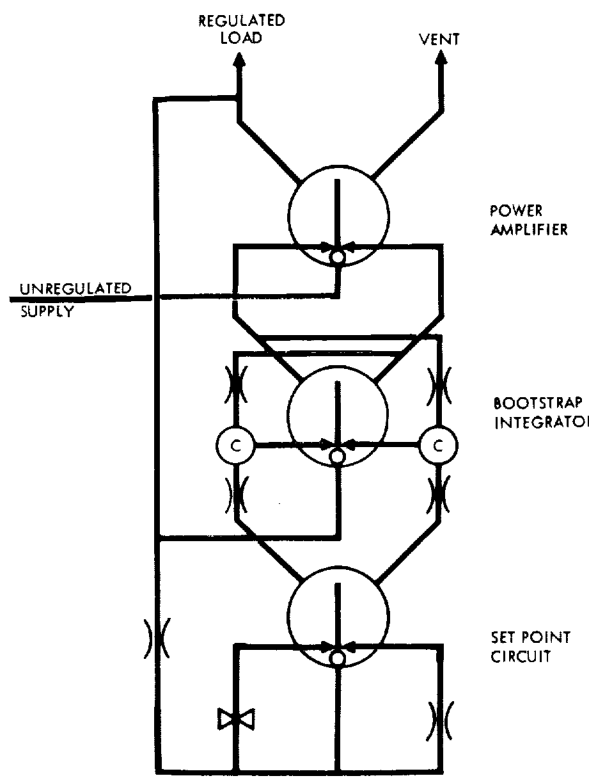


Figure 8-107. Proportional Pressure Control System

This type regulator is capable of operating over a 20 to 1 turndown range, however, it is limited to fixed area loads. Another drawback is that volume V_1 must be considerably larger than the stored volume, and consequently this design is impractical where space is at a premium.

8.6.4.7 Hybrid Regulator - It becomes obvious, that one approach which avoids the limitations imposed by a single storage tank is to use a variable area as the primary pressure dropping element. The variable area, which must be mechanically positioned, departs from the stated goal of having a pure fluid system with no moving parts. However, the concept appears to represent a practical means of obtaining a high turndown range with a minimum of moving parts and still retaining the other desirable features of a pure fluid system.

A typical hybrid regulator is shown in Figure 8-106. Tank pressure is dropped to a nearly constant supply by the variable mechanical orifice, which essentially increases in area as tank pressure decreases. The vented jet amplifier can then easily adjust the turndown of the nonvented vortex amplifier to accurately regulate the load pressure. This is possible because the effective turndown requirements of the nonvented vortex amplifier are drastically reduced by the variable mechanical orifice.

This type regulator should be capable of operating over an effective turndown range of 20 to 30 to 1. With careful design, the variable area orifice can be made extremely reliable, therefore this hybrid regulator can be effectively used until the state of the art evolves an acceptable pure fluid regulator.

8.6.4.8 Proportional Pressure Control System - A schematic of a fluidic feedback system which can be used as a pressure regulator is shown in Figure 8-107. The set point pressure is obtained by connecting the regulated pressure to the supply and the controls of a proportional fluid amplifier. A linear capillary resistor is inserted in one control leg and a nonlinear orifice restrictor in the other. The values of these resistors are adjusted so that the amplifier is zero (at null) at the desired regulated pressure. The differential output of the set point amplifier is fed into a bootstrap integrator, i.e., a proportional amplifier with positive feedback resistors which are adjusted to provide an integrating operation. The output of the integrator is then connected to the control ports of a proportional power amplifier. Regulated fluid is supplied to the load through one output leg of the power amplifier, and proportionally dumps to atmosphere through the other output leg when the load flow demand is decreased. The unregulated pressure source usually is used to supply the power jet of the power amplifier and the other amplifiers are powered from the regulated source.

This type regulator has extremely low power efficiency (25 to 50 percent), because of the venting nature of proportional amplifiers and the fact that it vents to atmosphere to maintain the regulated pressure during low demand periods. However, because of the bootstrap integrator, extremely fine pressure regulation is possible depending on the accuracy and gain of the pressure reference. One possible improvement is the use of the proportional set point and integration circuits to drive a vented jet controlled vortex valve.

8.6.4.9 New Regulator Concepts

Vented Jet-Vortex Amplifier Regulator - A possible method of utilizing a vented jet as a regulator is shown in Figure 8-108. This device consists of an in-line vented jet with the vent cavity controlled by a nonvented vortex amplifier. The nozzle to receiver spacing of the vented jet should be close (less than 0.6 times the nozzle diameter) and the diffuser section of the receiver should be carefully designed for good pressure recovery.

The operation of the device depends on the fact that at any supply pressure P_S there exists a region of operation in which output flow m_O and vent pressure P_V can be varied significantly while maintaining almost 100 percent pressure recovery (i.e., $P_O \approx P_S$). A nonvented vortex amplifier is used to control the vent flow and pressure in such a manner as to extend the limits of this high recovery region beyond those obtainable with vent flow flowing through a fixed orifice. For example, as a pressure regulator with fixed supply flow $\dot{m}_S$, operation is as follows:

Because $\dot{m}_S$ is fixed and nozzles A and B are choked (at sonic velocity), the supply pressure P_S and the vortex amplifier control flow $\dot{m}_C$ are fixed. If it is then assumed that the vented jet is initially operating in the high recovery region ($P_O \approx P_S$), should the load impedance decrease, the output flow $\dot{m}_O$ increases and the vent pressure P_V decreases. However, because of the fixed control flow $\dot{m}_C$ the vortex amplifier presents a higher impedance to vent flow at low values of P_V than at high values. Actually if P_V drops below a certain critical value, the vortex amplifier goes into complete turndown and vent flow becomes zero. Therefore, the vortex amplifier retards the decrease in vent pressure and maintains vented jet operation in the high pressure recovery regime for a broad band of output flows.

As the output impedance increases, the critical point occurs when nozzle B (Figure 8-108) unchokes, after which a further increase in load impedance will affect the flow source. In this case, however, the vortex amplifier tends to retard the increase in vent pressure, and actually allows lower output flows (even backflow) before nozzle B unchokes.

This device has very low output impedance, constant input impedance, and high pressure recovery. As such, it is a fluidic analog of a cathode follower stage. In general, the device can be used wherever it is desirable to isolate the effects of a variable load on a pressure-flow source. It can be used to convert a load-sensitive device into a load-insensitive device with no significant sacrifice in output pressure. A particular application of the device is as a pressure regulator, since when it is supplied by a constant flow source, it will maintain a near constant output pressure on a downstream variable load. It should also be useful as a relief valve, in that the downstream load could be a flow source as well as a flow sink.

Preliminary tests were completed with a vented jet regulator operating with a constant supply flow. An output pressure variation of 4 percent (±2 percent regulation band) was obtained with a load flow variation of 0 to 67 percent of the supply flow (Figure 8-109). Subsequent tests indicated that pressure regulation could be maintained even with significant reverse flow from the output port.

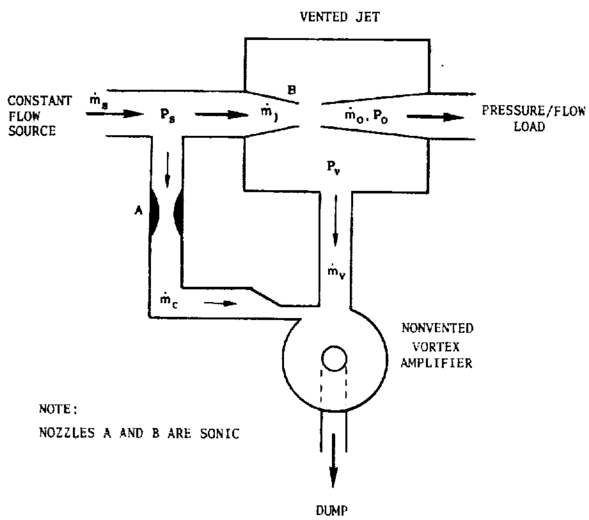


Figure 8-108. Vented Jet Regulator Concept

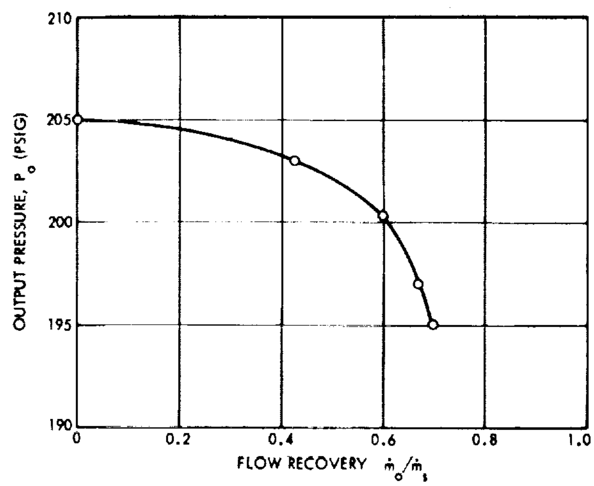


Figure 8-109. Vented Jet Regulator Performance

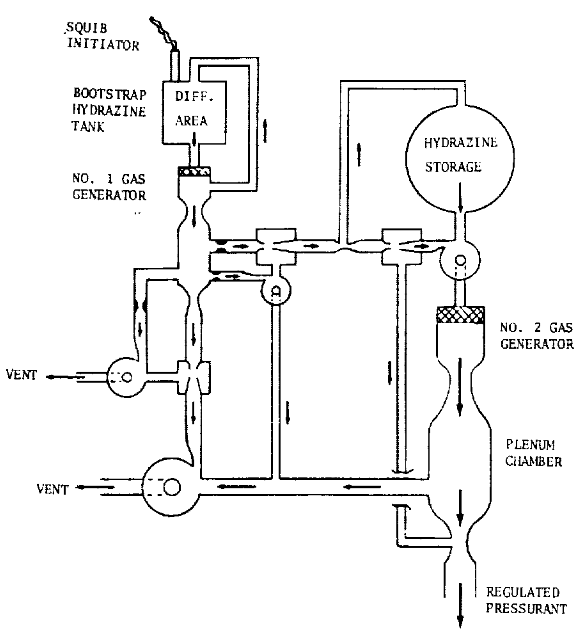


Figure 8-110. Monopropellant Gas Generator System

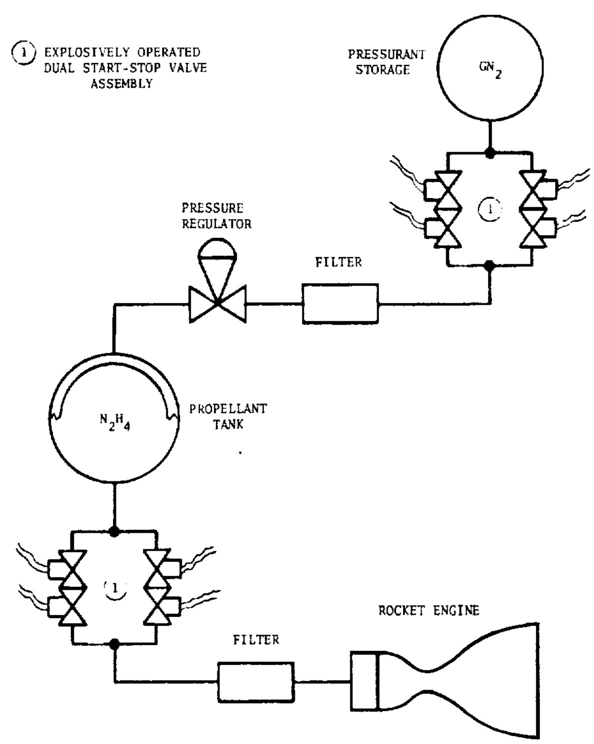


Figure 8-111. Baseline Monopropellant Hydrazine Propulsion System

Monopropellant Gas Generator System - The pressure regulation capabilities of the vented jet-vortex amplifier combination suggest the use of the device as a regulator in a monopropellant gas generator system (Figure 8-110). This pressurization subsystem is conceived as a two-stage monopropellant hydrazine system which provides pressurant for propellant tanks and the working fluid for a fluidic control system. It can accurately regulate the pressurant over a wide flow range, and the estimated duty cycle for the rocket engine firings is about 20 percent.

8.6.5 Propulsion Subsystem Application Study

This study was concerned with the application of fluidics to a typical spacecraft propulsion subsystem in the 50 to 1000 pound thrust range. A baseline propulsion system was selected and initial consideration was given to replacement of the pressure regulator in the baseline system with a fluidic regulator. Several alternate fluidic approaches to the baseline system were also conceived and a tradeoff study was performed.

8.6.5.1 Baseline Propulsion System - The Mariner Mars 1969 Propulsion Subsystem was selected as the baseline system for this study. This system (Figure 8-111) is a regulated pressure fed, fixed thrust, monopropellant hydrazine propulsion system which is a prime example of a well-designed, refined, and proven system. Principal subsystem components are a high pressure gas reservoir, a pneumatic pressure regulator, a monopropellant storage tank, and a rocket engine. The explosively operated start-stop valve assemblies in the pressurant and propellant lines each consist of two normally open and two normally closed valves providing a capability for two cycles of engine start and stop operation.

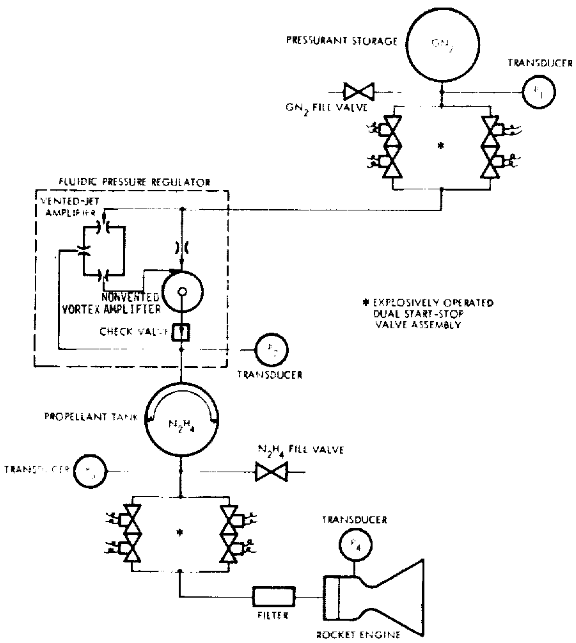
8.6.5.2 Fluidic Subsystem - Alternate approaches to the baseline propulsion system were selected on the basis of using fluidics exclusively for pressure regulation and/or propellant tank pressurization. In all, six alternate subsystem configurations were devised and they collectively employ three basic means for application of fluidics to the baseline propulsion system. These three basic means are as follows:

1. The fluidic regulation of gas pressure (using either inert stored gas or decomposed hydrazine) in a positive expulsion hydrazine storage tank -- Cases I, IV, and VI.

2. The fluidic regulation of liquid hydrazine flow rate to the engine, using the liquid hydrazine pressure for control -- Cases II and V.

3. The fluidic regulation of liquid hydrazine flow rate to the engine, using gas (in this case, both stored inert gas and decomposed hydrazine) -- Case III.

The six subsystems, Cases I through VI, are shown schematically in Figures 8-112 through 8-117, and described in detail in Reference 11. It should be noted that each of the approaches selected are based on non-fluidic propulsion subsystem configurations for which experimental or laboratory feasibility has been demonstrated. All approaches therefore represent demonstrated state of



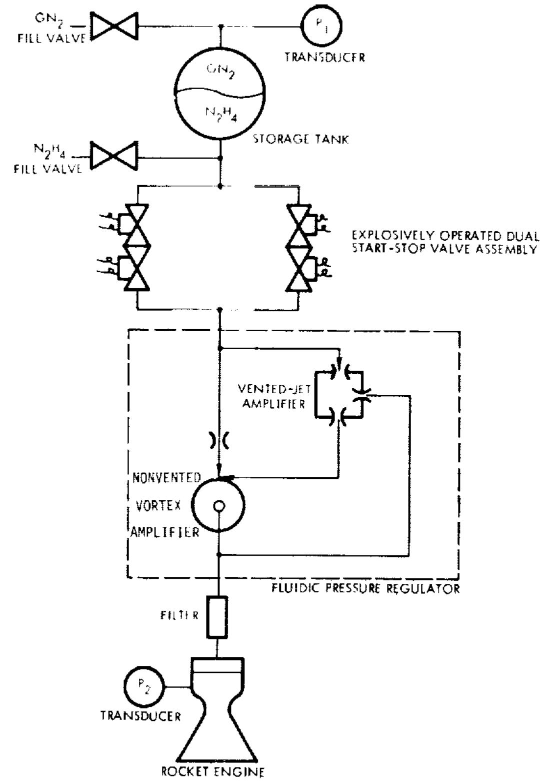
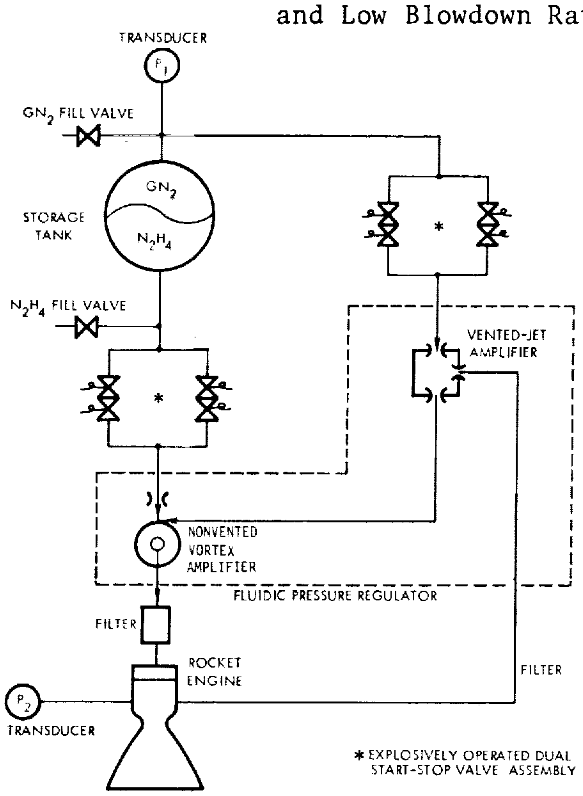


Figure 8-112. Case I - Gas Regulator and Low Blowdown Ratio

Figure 8-113. Case II - Propellant Regulator and Single Tank Blowdown



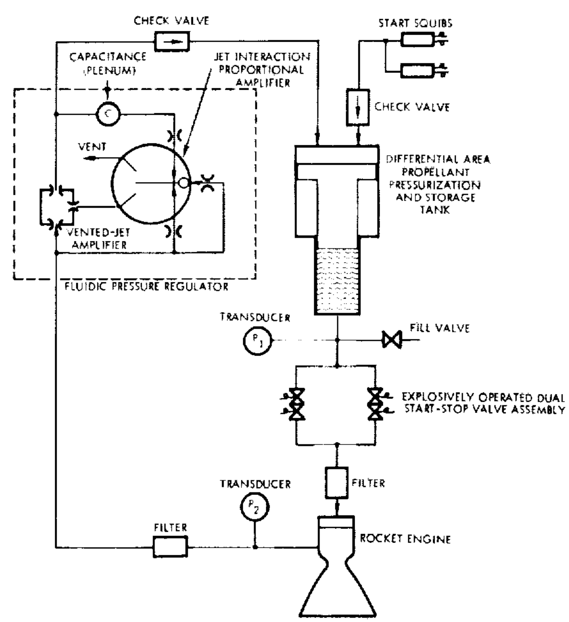


Figure 8-114. Case III - Propellant Throttle and Single Tank Blowdown

Figure 8-115. Case IV - Single-Stage Bootstrap

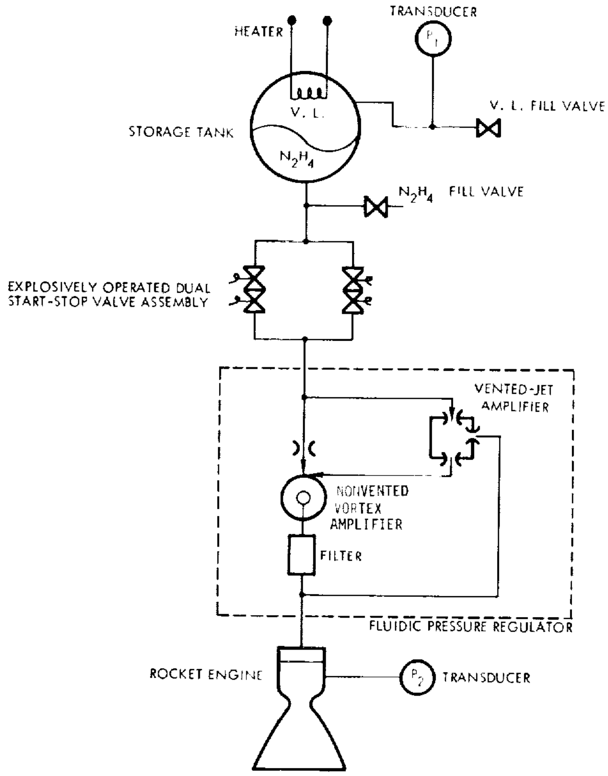


Figure 8-116. Case V - Volatile Liquid Expulsion

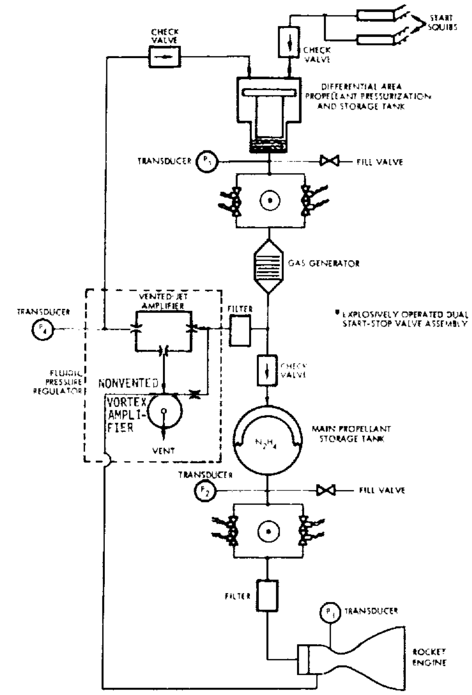


Figure 8-117. Case VI - Two-Stage Bootstrap

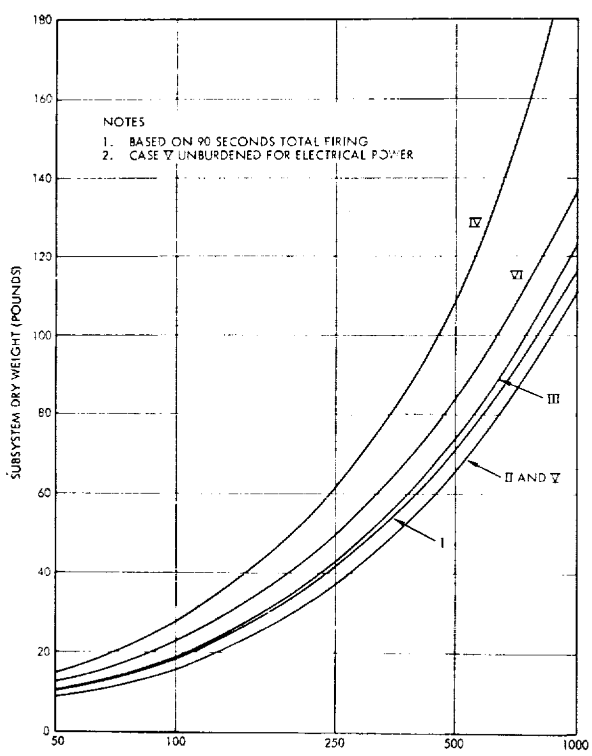


Figure 8-118. Propulsion Subsystem Dry Weight Comparisons

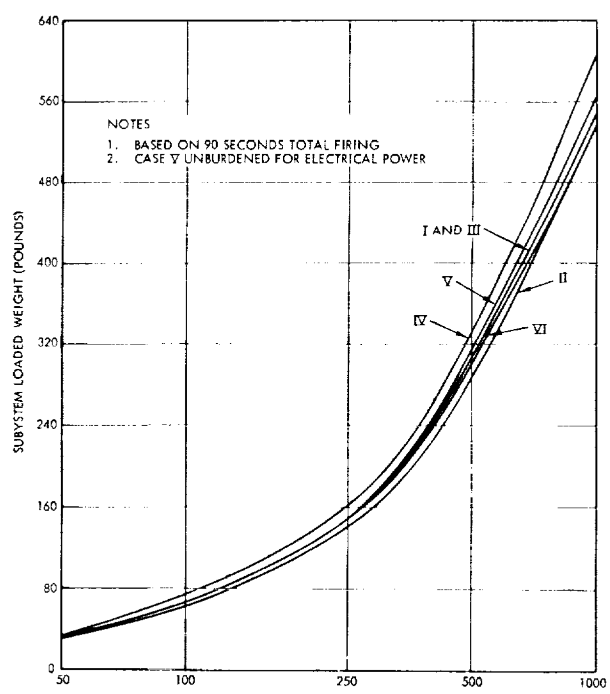


Figure 8-119. Propulsion Subsystem Loaded Weight Comparisons

the art technology except for the fluidic controls. The baseline system with a hybrid mechanical/fluidic pressure regulator was not included in this tradeoff study inasmuch as it departs from the form of the other approaches which are entirely fluidic in their means of regulation and pressurization.

8.6.5.3 Weight Analysis and Estimates - The derivation of equations and estimating procedures for the weights of the spherical tanks, differential area bootstrap tanks, pressurant gas, and propellant are given in Reference 11 along with a complete weight breakdown for each of the six cases and for each of three thrust levels. The thrust levels selected for subsystem weight evaluation were 50 pounds, 250 pounds, and 1,000 pounds. In this way, it was possible to plot a family of curves for subsystem weight versus engine thrust level. Using the weight breakdowns, two such families of curves were plotted, one for subsystem dry weights and the other for subsystem loaded weights. The difference includes the weight of propellant (liquid hydrazine), pressurant gas (GN_2) for the blowdown systems, and volatile liquid for the volatile liquid system.

The dry and loaded weight comparisons are presented in Figures 8-118 and 8-119. Referring to these figures, it is interesting to note that the relative positions of the six cases do not remain the same for the dry weight plots as they are for the loaded weight plots. On the other hand, there are no crossovers even though there are some end point intersections and overlapping of individual curves. The results shown graphically in these two plots are combined into one comparative rating for subsystem weight in the tradeoff summary (Table 8-9).

8.6.5.4 Subsystem Dynamics and Operational Complexity - Servo block diagrams for each of the six cases were generated primarily to compare operational complexity and to achieve some measure of insight into the operation of each of the subsystems as a feedback control system. These diagrams served as the basis for comparison of dynamic performance and as partial basis of comparison for simplicity in assigning the ratings for the tradeoff summary (Table 8-9).

8.6.5.5 Tradeoff Summary - An attempt has been made to present in tabular form the results of these application studies; i.e., results in terms of a tradeoff. This is shown in Table 8-9 where each case (approach) is rated numerically against the others with respect to several parameters. The parameters tabulated are weight, space, simplicity, state of the art, development cost, and dynamic performance. The rating system is such that a "1" indicates the best of the six cases for a particular parameter and a "6" indicates the worst. Hence, Case II is the simplest while Case VI is the most complex. Case II also has the fastest and probably most stable response, while Case VI is the slowest and most difficult to synthesize for stable operation. No attempt was made to draw any conclusions as to which is the best all around system approach since that would constitute only an academic exercise, and actual selection of a particular approach should be based on the application at hand. However, such an indication might best be obtained by summing the rating numbers in each column. The lower the sum total for any one case, the more it has to offer on an "all around" basis.

Table 8-9. Tradeoff Summary - Propulsion Subsystem Fluidic Application Studies

Parameter	Case I	Case II	Case III	Case IV	Case V	Case VI
Weight*	2	1	3	6	5	4
Space	6	1	4	3	2**	5
Simplicity	5	1	3	4	2**	6
State of the Art	1	4	3	2	6	5
Cost (Development)	3	2	1	5	4	6
Dynamic Performance	3	1	4	5	2	6
TOTALS	20	10	18	25	21	32

*Both dry and loaded weights were considered in arriving at the ratings indicated.

**These ratings are not penalized for electrical power which was presumed available and located elsewhere.

These tradeoffs were determined on the basis of a 50 pound thrust system, however, for all practical purposes the results apply equally well to any system in the range of 50 to 1000 pounds thrust.

8.6.5.6 Results and Conclusions - Referring to the tradeoff summary (Table 8-9), it is clear that Case II is superior to the others in most respects, except for state of the art. This is because Case II (also Case V) utilizes a propellant operated fluidic pressure regulator which involves operation of the vented jet amplifier on hydrazine. To date, the vented jet has been tested on water, but only enough to verify operation at relatively low pressure gains. Therefore, it is important to note that the future application of fluidics to propulsion systems will require considerable testing of fluidic devices and circuits with propellants if optimum design concepts are to be realized.

The variability in fluidic regulator configuration arrived at in this study indicates a need for comparing these different approaches on their own merits. For example, the six subsystems conceived during the study include 5 different types of fluidic regulators, which could be interchanged between systems. Numerous other regulator configurations are possible with the use of gas controlled liquid operated fluidic elements. Evaluation of the various regulator concepts requires a major effort which entails relative performance with respect to accuracy, operating range, dynamic operation, efficiency, etc. It is also not the intention of this study to rule out the applicability of the hybrid regulator, which was omitted from this study so that each case could be evaluated on a common (no moving part) basis. If found practical, the hybrid regulator has much to offer.

The application of fluidics to the baseline propulsion system is limited by the lack of component performance information in broad operation ranges and with liquids. Another complication is the requirement for a dual-start system which precludes the use of a conventional fluidic system with continuous overboard venting. As a result, each of the systems analyzed were designed to operate without overboard vents or with venting only during engine operation as was the case with the bootstrap gas generation systems. There are several significant conclusions that can be drawn regarding the application of fluidics to systems of the type studied.

1. Those fluidic devices which lend themselves to propulsion subsystem application require considerable testing and development on liquid propellants to reach an acceptable state of development.

2. New devices may be required which use gas to control liquids with no loss of the liquid media and preferably with no intermixing of the gas and liquid media.

3. Component performance data in the range of 50 to 1000 psig is lacking and in many cases normalized performance curves would be desirable.

4. The hybrid fluidic regulator concept would be the best choice if the accuracy problem can be resolved.

5. The selection of a fluidic subsystem probably should be delayed until sufficient performance information is available to verify predicted subsystem performance.

6. The application of fluidics to the functions of tank pressurization and pressure regulation can be pursued independently of the propulsion subsystem configuration itself.

8.6.6 Gas Pressure Regulator Study

The pressure regulator in the baseline propulsion system (see Section 8.6.5.1) is a modulating pressure reducing regulator. It is a key component in that its function is to hold the set point pressure within $\pm 1\%$ over the full pressure decay range of the pressurant storage tank. The tight regulation and lockup characteristic required are achieved through the use of Belleville reference springs and a hard poppet and seat. To assure consistently accurate regulation with minimum hysteresis, mechanical function is minimized by the flexural support of the push rod between the Belleville reference spring assembly and the sapphire poppet ball.

The primary reason for considering the use of a fluidic pressure regulator in this application, is that it should be simpler and have few, if any, moving parts. As a consequence, longer storage life, higher reliability and greater environmental tolerance could result. Improvements in size, weight, and cost are also possible.

8.6.6.1 Baseline Regulator Specifications - The important operational requirements of the baseline regulator are summarized below:

1. Working Fluid: Pressurant shall be gaseous nitrogen conforming to Federal Specification BB-N-411B, maintained between 35°F and 90°F.

2. Supply Pressure Variation: 3600 psia to 360 psia.

3. Outlet Pressure: 308 $\pm$ 3 psia when flowing 0.006 pounds per second of GN_2 at normal temperature (65°F to 95°F). A maximum variation of $\pm$ 5 psia is allowable when the regulator is subjected to the ambient temperature extremes of 14°F and 167°F.

4. Response: A supply pressure rise from 0 to 3600 psia in 2 millisecond shall not affect operation or performance.

5. Lockup Pressure: Seven percent or less above the nominal regulated pressure at inlet supply pressures in the range 3600 psia to 375 psia.

6. Internal Leakage: Ten scc/hour of GN_2 maximum over the supply pressure range 360 psia to 3600 psia.

7. External Leakage: Zero (defined as 1 scc/hour of GN_2 maximum).

8. Operating Life: Capable of maintaining the specified outlet pressure for a total period of 90 seconds maximum, and a maximum of two starts.

9. Storage Life: Minimum storage life shall be two years in an unpressurized condition while exposed to a temperature range of 0°F to 125°F and a relative humidity up to 95 percent. In addition, 350 days in the fully pressurized condition while exposed to the temperature range of 35°F to 90°F.

10. Environments, Non-Operating: The regulator shall operate satisfactorily after exposure to the vibrational, shock, acceleration, acoustic, radiation, etc., environments normally encountered during earth orbital launch maneuvers.

11. Environments, Operating: The regulator shall operate satisfactorily when exposed to a space environment, including vacuum conditions of 10^{-8} to 10^{-14} torr, positioned in any attitude, and zero gravity.

8.6.6.2 Preliminary Considerations - Previous state of the art surveys and application studies have shown that it is presently impractical to implement a modulating pressure reducing regulator by fluidic means. This particularly applies to large blowdown range operation and is a consequence of the following:

1. No fixed area orifice with appreciable pressure drop can be installed in the main flow path if the pressure regulator is to throttle flow over a wide range of supply pressure.

2. No known fluidic device, other than the nonvented vortex amplifier, is capable of throttling flow with acceptable efficiency. The vortex amplifier normally requires a source of control pressure higher than the supply pressure.

3. The use of a fixed area orifice to drop the nonvented vortex amplifier supply pressure below the storage tank pressure so as to obtain the necessary control to supply pressure ratio is impractical. This follows from the fact that the pressure dropping orifice must become sonic during tank blowdown and consequently cannot be controlled by the downstream vortex amplifier even for a slight decrease of tank pressure.

4. It has also been shown that no significant increase in turndown will result from connecting vortex amplifiers in series.

One possible pure fluid regulation scheme utilizes dual volumes, such that gas for vortex amplifier control purposes is stored separately at higher pressures. However, the necessity of having to stage gas at two different pressure levels must be considered a disadvantage. Another problem is the possibility of leakage disturbing the required balance between the weights of gas stored in the two volumes. It is also possible to use other approaches to pure fluid regulation if space is not at a premium such as single-lag and double-lag circuits (Reference 19). The single-lag regulator requires little additional space, but is limited in blowdown range. The double-lag regulator offers a reasonable blowdown range but requires the most space and is limited to fixed area loads. Actually, one lag volume is usually considerably larger than the stored volume.

It becomes evident that a variable area primary orifice must be used if the regulator is to be of minimum size and capable of operating over a large blowdown range. The variable area, which must be mechanically positioned, departs from the goal of a pure fluid system with no moving parts. However, a hybrid of this type offers a practical means of obtaining a high turndown range with a minimum of moving parts and still retaining the other desirable features of a fluidic system.

8.6.6.3 Hybrid Fluidic Regulator Concept - The hybrid regulator shown schematically in Figure 8-120 was subsequently chosen as the most practical fluidic replacement for the baseline regulator. Tank pressure is dropped to a nearly constant supply pressure by the variable area orifice, which increases in areas as the tank pressure decreases. Consequently, the turndown requirements of the nonvented vortex amplifier are drastically reduced so that a subsonic fixed area orifice can be placed upstream of the amplifier. The vented jet can then easily adjust the turndown of the vortex amplifier to accurately regulate the load pressure, in addition to providing an absolute pressure reference when venting directly into the load. This regulator also fulfills the requirement for zero leakage since all flow passes through the load.

The poppet for the variable area orifice is suspended between a spring diaphragm and a combination spring bellows and seal. Since the poppet is essentially suspended on two flexures, it cannot physically contact or slide on any surface and is free from friction. To meet the low internal leakage requirement, the poppet and seat could be ground and lapped, however, the suspension would have to be rearranged and a preload spring added.

Considering that the primary function of the variable area orifice is to reduce the tank pressure to a nearly constant supply pressure, no stringent fabrication and calibration requirements need to be imposed on the poppet, seat, and flexural supports. Since friction is virtually nonexistent, hysteresis should be reduced considerably under all operational conditions. Outlet pressure variations due to the specified ambient temperature extremes should also be substantially reduced because of the intrinsic insensitivity of both the nonvented vortex amplifier and vented jet to fluid temperature variations. Finally, overshoot in the set pressure during startup should be minimized because of the response time (less than 1 millisecond) of vortex amplifiers in the size required for this application.

8.6.6.4 Hybrid Regulator Sizing - Preliminary sizing of a hybrid regulator to meet the baseline regulator requirements was completed. A summary of the calculations involved is presented in Reference 11 and the important set point parameters are listed in Figure 8-121.

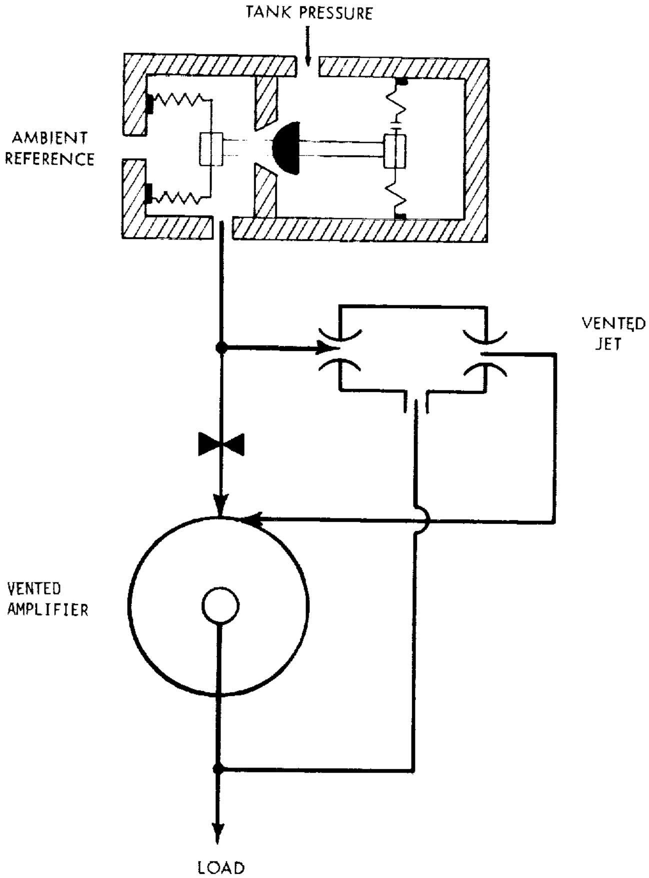
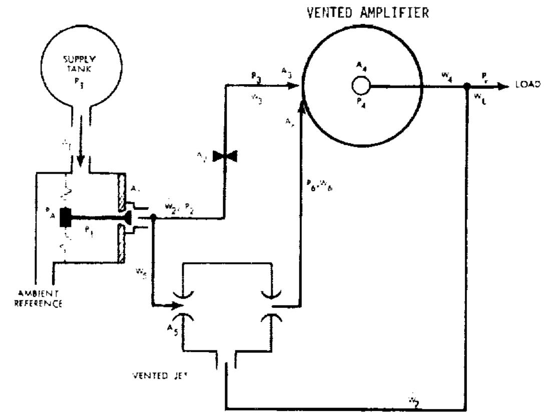


Figure 8-120. Hybrid Fluidic Regulator Concept



STATION	PRESSURE, P (psia)	FLOWRATE, $\dot{W}$ (lb/sec	AREA, A (in^2)	DIAMETER (in)
Tank	3600/410	.006		
1	3600/410	.006	.00009/.00462	.011/.056
2	400	.00462	.000804	.032
3	330	.00462	.00482	.078
4	322	.00508	.002035	.051
5	400	.00138	.000216	.017
6	344	.000462	.000163	.014
7	308	.00092		
Load	308	.006		

Figure 8-121. Hybrid Regulator-Set Point Parameters

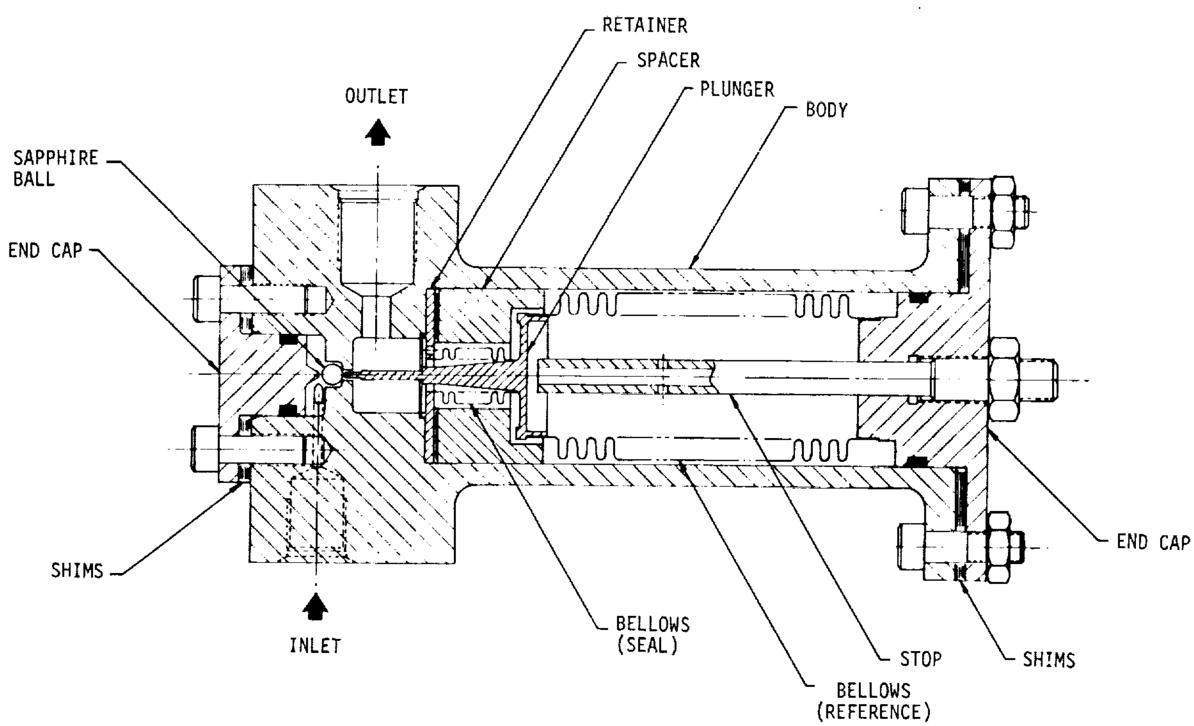


Figure 8-122. Hybrid Regulator Mechanical Stage

The vortex amplifier has a chamber diameter of 0.50 inch and the vented jet supply nozzle a diameter of 0.017 inch. Considering the small size of these elements, a hybrid regulator of this type should have a maximum envelope size of 1 inch in diameter by 2 inches long and a weight of about 1/2 pound. This compares favorably to the baseline regulator which has an envelope of about 3 inches in diameter by 3 inches long, and a weight of about 1-1/2 pounds.

8.6.6.5 Hybrid Regulator Performance - It is logical to believe that the hybrid regulator will meet the outlet pressure requirements even at the ambient temperatures extremes specified. However, the vortex and vented jet amplifiers must function in unfamiliar operational regimes where very little performance information is presently available. Both elements will require some development, which will include documentation and optimization in the required operational regimes.

Lockup and internal leakage requirements were not considered in this preliminary study. However, the poppet and seat can be made similarly to those on the baseline regulator. External leakage will still be zero.

An important consideration is that the time response of the regulator will depend on the response of the vortex amplifier-vented jet combination, since the variable area first stage is essentially isolated from the output. The time response of the vortex amplifier alone is less than 1 millisecond with a dual exit. Since the turndown requirements for the vortex amplifier have been materially reduced by the variable area inlet orifice, a single exit nonvented vortex amplifier could be used so that propagation delays between the vortex amplifier and vented jet are held to a minimum. The overall regulator response would then be between 1 and 2 milliseconds.

8.6.6.6 Hybrid Regulator Design - A dynamic analysis of the hybrid regulator mechanical stage was undertaken and the results are reported in Reference 11. The analysis is strictly parametric; i.e., there is no numerical analysis presented. What is given is a servo block diagram for the regulator mechanical stage, followed by derivations of nonobvious transfer functions. In addition, the effective damping ratio of the system at its natural frequency is expressed as a function of the regulator design parameters. Similarly, each of the constants appearing in the regulator block diagram is expressed in the analysis as a function of the regulator design parameters. By referring to this analysis, the engineer can proceed with synthesis of the regulator using classical feedback control theory to assure the required margin of stability, dynamic response, and accuracy in the final design.

An engineering layout of the mechanical stage (Figure 8-122) was prepared following the general configuration evolved in Reference 11. The small diaphragm separating the regulated pressure cavity from the feedback pressure cavity was mechanized by a small bellows and a lateral flexural support. This design was conceived just for construction of an experimental model, since it is based on elements that were either on hand or are readily available; i.e., lateral flexural support and bellows, respectively.

The regulator valve itself is of a poppet-type configuration where the poppet is an unattached sapphire ball. The ball is driven off its seat by a narrow valve stem and is opposed by supply pressure rather than a spring. There are no sliding parts anywhere in the regulator; all supports and seals are achieved with flexural members. Pneumatic clamping is provided by an orifice connecting the regulated pressure cavity and feedback pressure cavity. The specific design presented in the engineering layout prepared incorporates a damping ratio of 0.06 which is more than adequate for this particular design.

8.6.6.7 Conclusions and Recommendations - The hybrid regulator, as presently conceived, should provide a substantial savings in size and weight over the baseline regulator. However, a severe propulsion system weight penalty is imposed if the vented jet amplifier is used in its best operational regime. Overboard venting may also be required to maintain the required regulator accuracy.

A preliminary search was made for a replacement for the vented jet. The only logical device found thus far is the momentum amplifier (Reference 17) which was developed by the Fluidonics Research Laboratory, Imperial-Eastman. The device appears to provide more than adequate pressure gain, however, the gain is negative; i.e., the output decreases as the control signal is increased. It is possible to produce a positive gain by biasing the device, but gain is sacrificed.

In concept the hybrid regulator is feasible. The design of the primary stage has been shown to be practical and straightforward. Additional effort is warranted in regards to the control loop around the vented vortex amplifier, which is the major stumbling block thus far. This is necessary, because the vented jet needs a much higher primary supply pressure to meet regulated pressure accuracy requirements, which would be a serious drawback in a systems application.

8.6.7 Propellant Flow Control Study

Throttling devices are required to facilitate the regulation and flow control of pressurants and propellants. Simple, reliable mechanical throttles were used in the hybrid fluidic controls considered in this study, with primary emphasis on the elimination of sliding mechanical parts. These devices can function without the overboard venting of propellants.

Fluidic throttling devices with wide flow control ranges require overboard venting. The use of a nonvented device, such as the vortex amplifier, is impractical because the control pressure has to be significantly higher than the supply pressure to effect throttling. This means that a separate source of supply fluid is required or the supply flow has to be dropped in pressure to make the controls effective. In the latter case, the throttling range is drastically reduced.

In the ideal sense, an efficient method of throttling in a single source fluidic system is depicted in Figure 8-123. Control flow is bypassed from the supply stream to power a fluidic controller which adjusts the throttling device on the basis of an internal reference signal or an external command signal from an electrical to fluid transducer. Vent flow from the controller is returned and combined with the output flow. The controller functions on the differential pressure across the throttling device, which presents

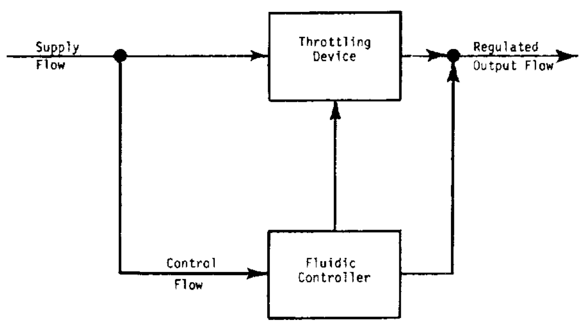


Figure 8-123. Concept of Single Source Fluidic Throttling

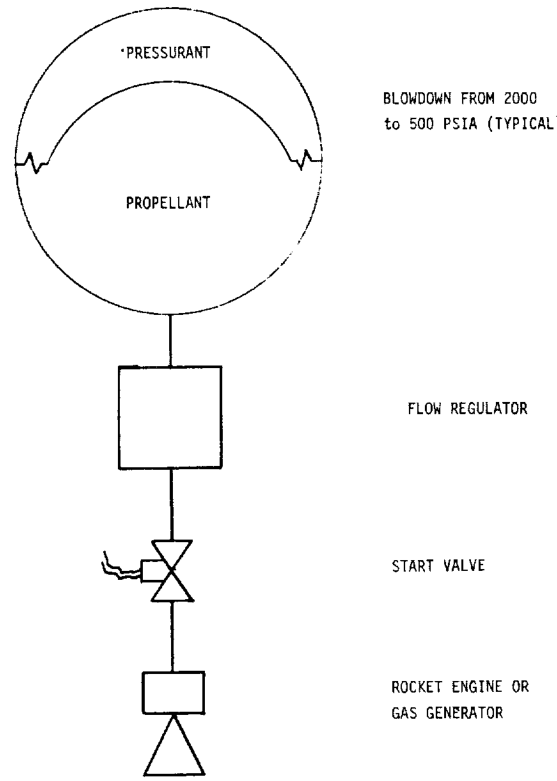


Figure 8-124. Typical Monopropellant Feed System

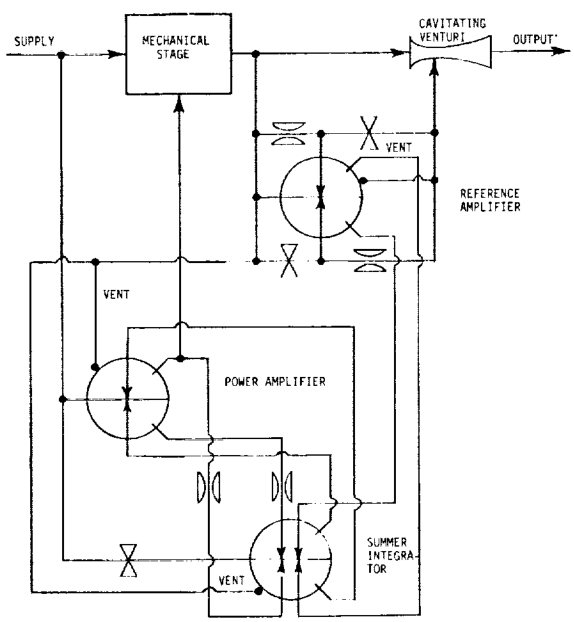


Figure 8-125. Hybrid Fluidic Flow Regulator

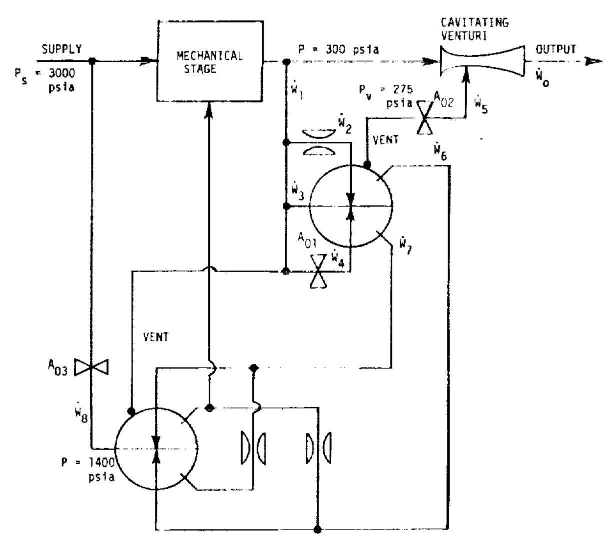


Figure 8-126. Simplified Hybrid Flow Regulator - Scheme I

difficulties in that the supply and output pressures can vary independently and the fluidic circuitry must be designed to function on a variable differential pressure. In addition, the throttling device is operated with a control pressure lower than the supply pressure, and without an overboard vent there is no way of establishing an absolute pressure reference for the fluidic controller.

With these criteria, a study was made, in particular, with regard to the fluid mechanics of internal flow. To date, three conceptual devices have been defined which show considerable promise and should be investigated further.

1. Bypass Venturi Throttle - This involves the injection of fluid in the low pressure throat section of a venturi, to throttle by an effective throat area change or induced cavitation.

2. Vortexing Conical Diffuser - The mechanism of swirling flow through a convergent-divergent nozzle can cause reverse axial flow and in the ideal case a pronounced reduction of mass flow and, in some cases, flow stoppage. This mechanism coupled with control flow at the minimum nozzle area, to modulate the degree of swirl, has excellent potential as a fluid throttle.

3. Cavitating Venturi Pressure Reference - A venturi section operated in cavitation has a relatively large cavitation bubble downstream of the throat which is essentially at the vapor pressure of the flowing liquid. In concept, the cavitation bubble would make a suitable nonventing absolute pressure reference for a fluidic controller if it can accept the reference signal flow without collapsing.

8.6.7.1 Hybrid Flow Regulator - Application Study - This study was concerned with defining the methods of fluidically controlling the flow of a liquid monopropellant in a typical feed system in conjunction with a simple mechanical throttle. A typical system is defined in Figure 8-124. The flow range of interest is 0.25 to 5 lb/sec which corresponds to a thrust range of 50 to 1000 pounds. Initial consideration will be given to a flowrate of 1 lb/sec (200 pounds thrust), however, the study data should apply equally well to the control of bipropellants such as diborane and oxygen difluoride.

A direct-acting mechanical flow regulator maintains a constant flow rate by keeping the pressure drop across a fixed orifice constant regardless of variations in either the supply or discharge pressures. This is accomplished by the use of a pressure balanced control valve which acts as a variable orifice downstream of the fixed orifice. The pressure drop across the fixed orifice is impressed across a sensing diaphragm which is mechanically coupled to the control valve. Any variation of the pressure drop across the fixed orifice will cause the control valve to change the variable orifice setting so as to restore the original pressure drop.

A fluidic mechanization of the basic direct-acting mechanical flow regulator is shown in Figure 8-125. The difference in the characteristics of a nonlinear and a linear resistor is detected by the reference amplifier which vents directly into the cavitating venturi. The error signal is summed with a positive feedback signal in the summer-integrator, which controls the power amplifier to position the mechanical stage. The regulator performs a flow regulation function, in that the fluidic circuit adjusts the mechanical stage to maintain the downstream pressure at a constant absolute level. It is presumed that the vent flow to the cavitating venturi is a constant.

A simplified concept of the flow regulator was conceived in an effort to reduce the number of active elements, as shown in Figure 8-126. Essentially this circuit involves the consolidation of the integrator and power amplifier functions in one amplifier, which presumes an amplifier with a high open loop pressure gain (>50) would be available. A preliminary sizing of this simplified concept was accomplished utilizing the catalog performance of a General Electric AW32 proportional amplifier to determine relative flow rates.

Presuming initially, for maximum reliability, that the minimum constriction in all circuit elements would be 0.015 inch diameter and that the differential pressure across nonlinear resistor A_{01} is 60 psi.

$$\dot{W}_4 = 21.9\ C_f\ d_{01}^2\ (\Delta P)^{1/2}$$

$$= 21.9 \times .6 \times (1.5)^2 \times 10^{-4} \times (60)^{1/2}$$

$$= 0.0228 \text{ lb/sec}$$

$\dot{W}_2 = \dot{W}_4$ when the set pressure is reached and $\dot{W}_3 = 10\ \dot{W}_2$ based on the AW32 amplifier characteristics.

$$\therefore\ \dot{W}_1 = \dot{W}_2 + \dot{W}_3 + \dot{W}_4$$

$$= 0.0228 + 0.228 + 0.0228$$

$$= 0.2736 \text{ lb/sec}$$

Since $\dot{W}_1$ is already 27 percent of the output flow, the differential pressure across A_{01} was reduced to 25 psi, Recalculating, $\dot{W}_1$ was reduced to 0.1776 lb/sec.

Continuing further, under quiescent conditions $\dot{W}_6 = \dot{W}_7 = 0.22$ lb/sec based on the AW32 amplifier performance, so that the vent flow

$$\dot{W}_5 = \dot{W}_1 - (\dot{W}_6 + \dot{W}_7) = 0.1336 \text{ lb/sec}$$

With this flowrate, the size of nonlinear orifice A_{02} becomes 0.0248 inch diameter. Further calculation at the maximum supply pressure of 3000 psia made it possible to determine system operating pressures as shown in Figure 8-126. The other important circuit parameters are $d_{03} = .0167$ inch and $\dot{W}_8 = 0.146$ lb/sec.

A review of the results of this preliminary sizing of the simplified flow regulator (Figure 8-126) indicated no particular problem with the size of circuit elements. Since the reference circuit vents ($\dot{W}_5$) only 0.1336 lb/sec it is possible that pressure regulation could be accomplished with a flow range of something <7.5. Flow range will improve at thrust levels greater than 200 pounds. There is some concern as to whether the cavitating venturi can handle the reference circuit vent flow which is about 15.5 percent of the main flow through the cavitating venturi. No data is presently available to determine the feasibility of this vent scheme. An important point concerning this regulator is that the control inputs to the integrator-power amplifier would have to function in an interaction region at a slightly higher pressure. This mode of operation does not appear feasible at present.

Based on the above, a second simplified hybrid flow regulator was conceived as shown in Figure 8-127. The primary difference in Scheme II, is that the integrator-power amplifier also was made to vent directly into the cavitating venturi. Therefore, the circuit elements were carefully sized to minimize vent flow. Circuit parameters were calculated as for Scheme I and included in Figure 8-127.

A total vent flow for Scheme II was found to be 0.1248 lb/sec which is only about 12.5 percent of the flow required for a 200 pound thrust monopropellant engine. The minimum nonlinear orifice size used was 0.012 inch in diameter, which would certainly be the smallest considered. The linear resistor in the reference circuit was estimated to be composed of 12 tubes, 20 inches long with an I.D. of 0.010 inch. As shown in Figure 8-127, all of the other circuit elements are of practical size, so that this scheme appears feasible for both flow and pressure regulation. For pressure regulation, an electrical to fluid transducer would be installed around the nonlinear resistor A_{02} in the reference circuit, so that the reference pressure can be varied on command.

To reduce the number of active elements even further, it would be better to introduce the reference resistors directly into the integrator-power amplifier as shown in Figure 8-128. However, this could not be done unless the amplifier has an open loop pressure gain >100.

The results of this study thus far have pointed up two basic requirements regarding circuit elements for the flow regulator.

1. A cavitating venturi capable of handling a vent flow of about 10 percent of the mainstream flow at a constant absolute pressure level.
2. A fluidic proportional amplifier with a pressure gain >50 and preferably >100.

8.6.7.2 <u>Hybrid Flow Regulator Concept</u> - A hybrid fluidic mechanization of the propellant flow regulator is shown in Figure 8-129. This regulator concept utilizing a mechanical stage to throttle the decaying pressure-flow source. The fluidic circuit provides the reference pressure signal and generates the error signal to control the mechanical stage. Bypass propellant is used to operate the fluidic circuit and is returned to the mainstream at the throat of a venturi section.

The high gain proportional reference amplifier in the fluidic circuit detects the difference in the pressure-flow characteristics of a linear and nonlinear resistor and generates a high or low differential error signal. The reference pressure point or regulator set point occurs when the differential

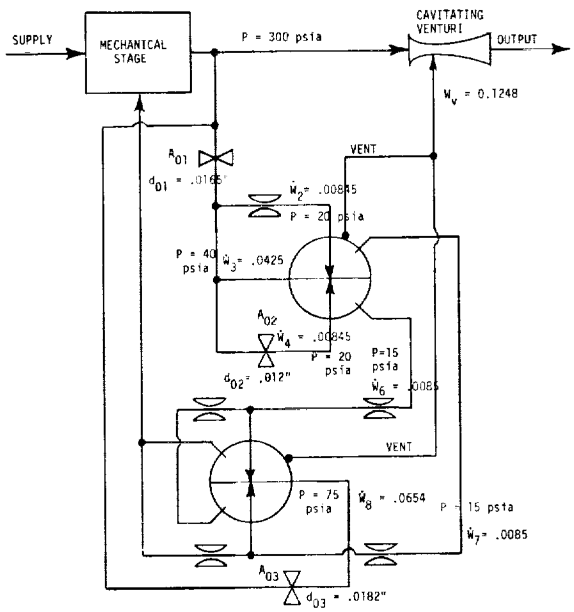


Figure 8-127. Simplified Hybrid Flow Regulator - Scheme II

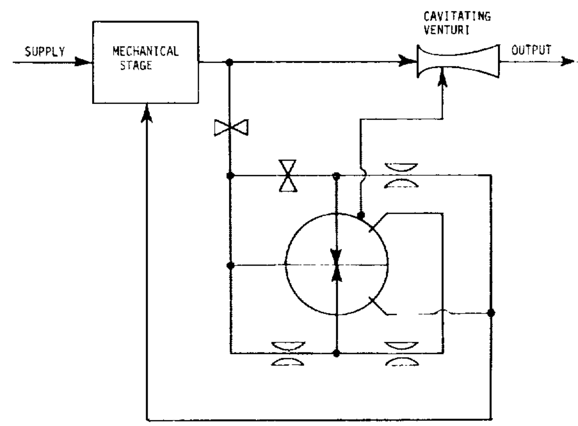


Figure 8-128. Simplified Hybrid Flow Regulator - Scheme III

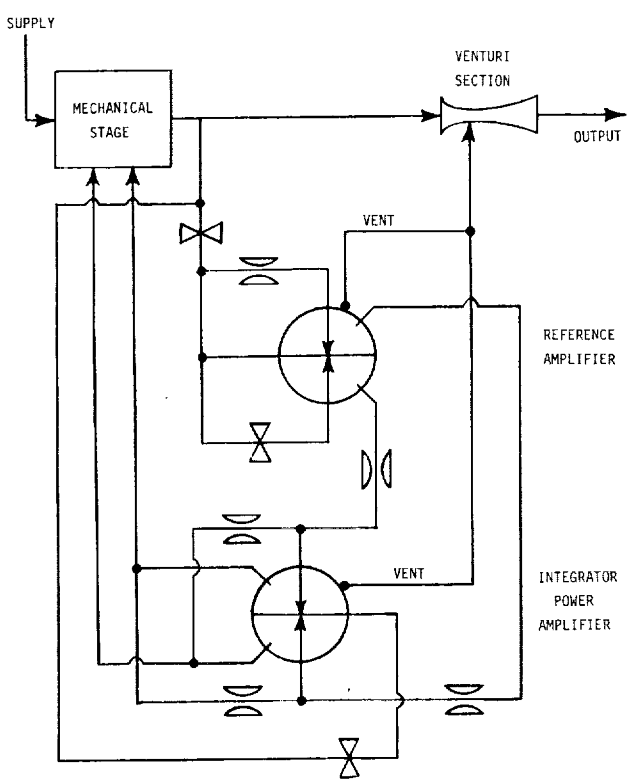


Figure 8-129. Hybrid Fluidic Propellant Flow Regulator

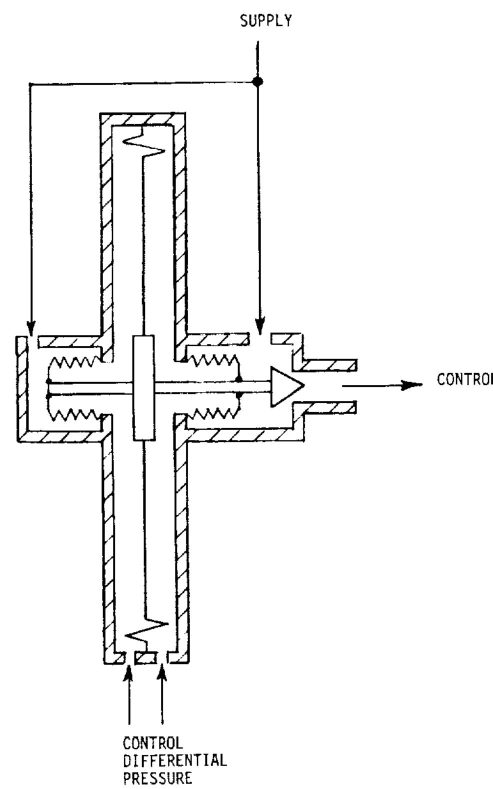


Figure 8-130. Balanced Mechanical Stage Concept

pressures and flows in both resistors are equal. The error signal is received at the integrator-power amplifier which integrates the error by the use of positive feedback and generates a differential output signal to control the mechanical stage directly. To change the regulated flow rate on command, an electrical to fluidic transducer could be installed in parallel with the fixed nonlinear resistor in the reference circuit. Fluidic proportional amplifiers used in this regulator should have open loop pressure gains >50. This minimizes the number of active fluidic elements required so that the vent or bypass flow to the venturi is held to a minimum. Pressure gains of about 100 have been demonstrated experimentally at the Harry Diamond Laboratories.

The venturi throat provides a constant pressure sump for the fluidic control circuit. Since the pressure and flow are kept constant, the static pressure at the venturi throat should also be constant. Another possibility is to operate the venturi section in deep cavitation, so that the bypass control flow is injected into the cavitation bubble which is essentially at the vapor pressure of the flowing propellant. This provides the further advantage of isolating the regulator from downstream conditions.

The mechanical stage is conceived as a simple poppet valve which is positioned by a pressure balanced diaphragm actuator (Figure 8-130). Pressure balancing is required to minimize the control power requirement and further reduce the control bypass or vent flow. High reliability is maintained by eliminating all sliding parts in the mechanical stage. This is achieved by suspending the poppet on flexures, i.e., a diaphragm and two bellows.

8.6.7.3 Advantages of the Hybrid Regulator

1. High reliability and long term storage capability in the space environment due to the elimination of all sliding parts.

2. The capability of adjusting the flow rate on command over a 5 to 1 flow range in a 200 pound thrust engine system, and over a broader flow range at higher thrust levels.

3. Can be operated by and stored wet with any liquid propellant.

4. Proportional control with positive feedback provides near constant control loop gain over entire supply blowdown range.

5. The cavitating venturi provides complete isolation from downstream conditions.

8.6.7.4 Applications of the Hybrid Regulator

1. Flow regulation of all liquid propellants.

2. Open and closed loop bipropellant oxidizer-fuel ratio controllers.

3. Wide range flow regulation on command or programmed.

8.7 FLUIDIC CONCEPTS AND DEMONSTRATIONS

8.7.1 Vented Jet Evaluation

A variable geometry vented jet was tested to determine the capability of this device in the operational range required for the hybrid regulator. The configuration and operating principles are reported in Reference 19. Referring to Figure 8-131, performance of the vented jet is related to the gap length, ℓ, and the vent to supply pressure ratio, P_v/P_s. Gap length is non-dimensionalized as a function of the supply nozzle diameter, D_s, i.e., the supply to output nozzle separation is specified as the ratio ℓ/D_s.

Previous evaluation of the vented jet was accomplished at P_v/P_s in the range from 0 to 0.7 and gap lengths from 0.5 D_s to 4 D_s. Typical performance with gaseous nitrogen and a gap length equal to D_s is depicted in Figures 8-132 and 8-133 for a 0.016 inch diameter and a 0.020 inch x 0.040 inch rectangular load orifice respectively. Pressure and flow recoveries at these orifice loads are shown in Figures 8-134, 8-135 and 8-136. The gain of this device is constant for a wide variation in load, however, the pressure recovery decreases slightly with increasing load flow. At $P_v/P_s > 0.3$ the pressure recovery is >90 percent with average loads. In controlling a vortex amplifier, the vented jet also has a self regulating characteristic, in that both the pressure recovery and flow recovery increase with increasing supply pressure. These features were what made the vented jet a logical choice for use in the gas pressure regulator (section 8.6.6).

For this application, the vented jet is required to operate at a P_v/P_s of 0.72 and a nominal pressure recovery of 86 percent. Previous tests at gap lengths $\geq$4 D_s indicated that the gain, $\Delta P_o/\Delta P_s$, of the device at the required P_v/P_s ratio was insufficient for use in the hybrid regulator control loop. However, data from a Bendix report indicated that the high gain region could be extended out to higher P_v/P_s by increasing the gap length (Figure 8-137). On this basis, testing of the vented jet at larger gap lengths was undertaken.

A new variable geometry vented jet was fabricated (Reference 11) and tested with gaseous nitrogen at gap lengths of 1.67 D_s to 7 D_s. The maximum pressure gain was found to be 0.6 at a gap length of 7 D_s for the required P_v/P_s of 0.72. It was also concluded that larger gap lengths would not provide a significant increase in gain. These tests have shown that the vented jet does not have a high enough gain at $P_v/P_s > 0.4$ to provide a tight enough control loop in the gas pressure regulator.

The use of the vented jet in the hybrid regulator would involve increasing the output pressure of the primary mechanical stage from 400 to 800 psia and the use of an overboard bleed. Each of these requirements would impose a severe weight penalty on the baseline propulsion subsystem and was felt impractical for this application. Modification of the vented jet configuration was also possible, but contemplated changes were major, required development, and only had a fair chance of success.

8.7.2 Electrical Interfaces

The mechanism by which an electric-field interacts with a fluid jet depends on the electrical and mechanical boundary conditions imposed on the system.

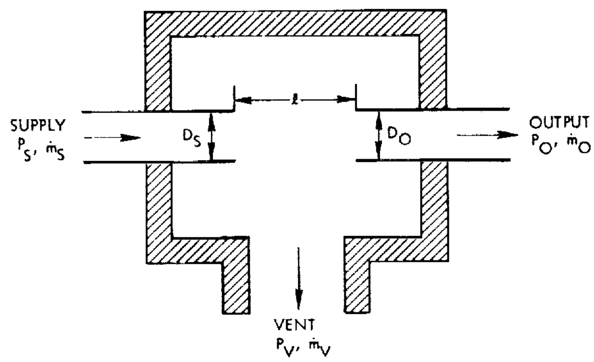


Figure 8-131. Vented Jet Amplifier Parameters

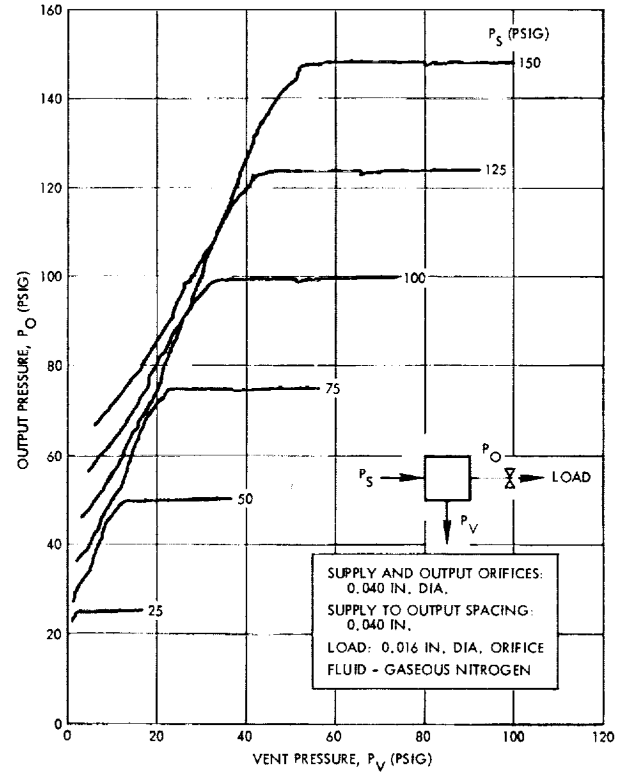


Figure 8-132. Model VJ-1 Vented Jet Performance (0.016" Diameter Load)

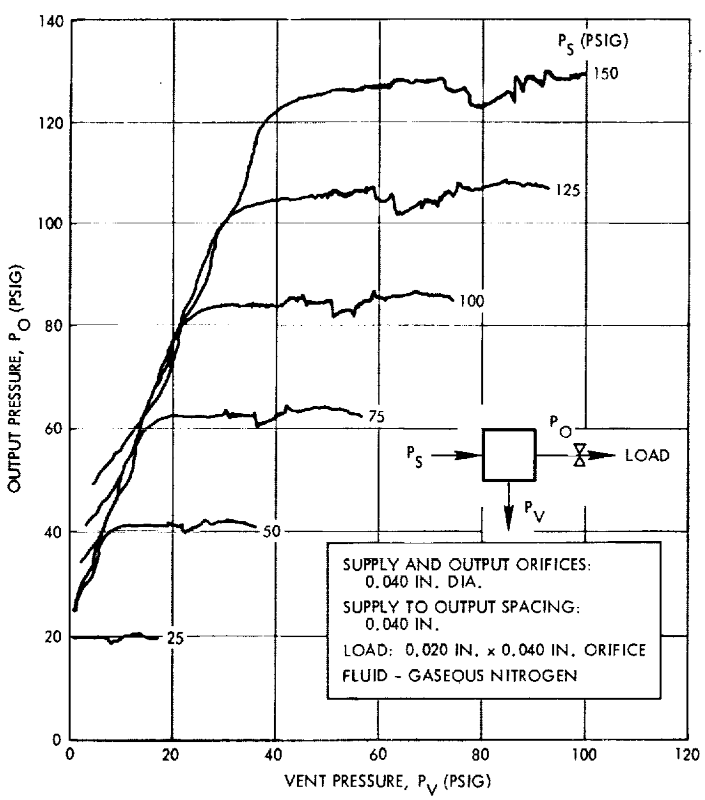


Figure 8-133. Model VJ-1 Vented Jet Performance (0.020" x 0.040" Load)

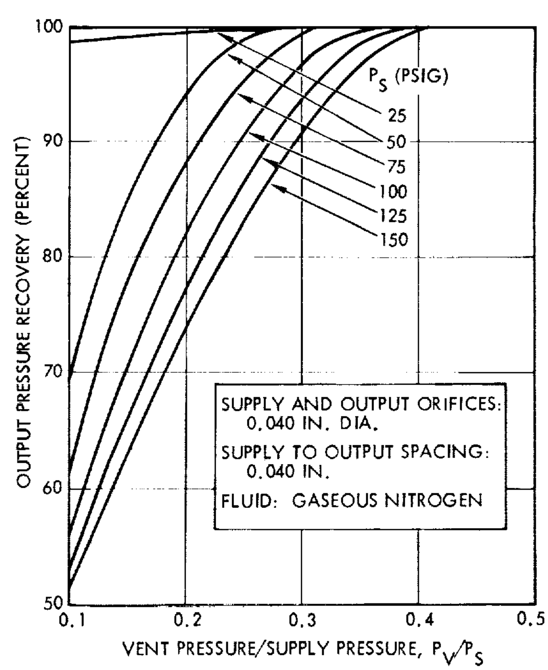


Figure 8-134. Model VJ-1 Vented Jet Pressure Recovery (0.016" Diameter Load)

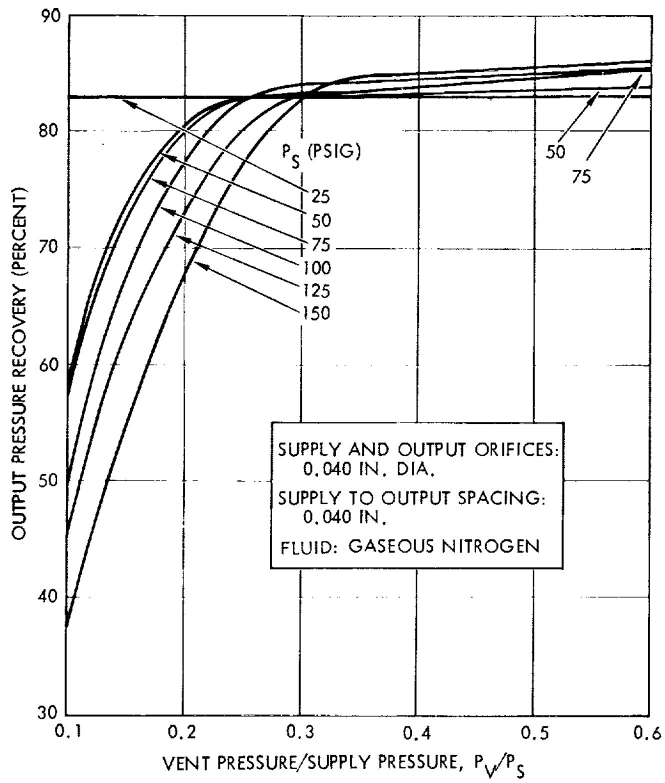


Figure 8-135. Model VJ-1 Vented Jet Pressure Recovery (0.020" x 0.040" Load)

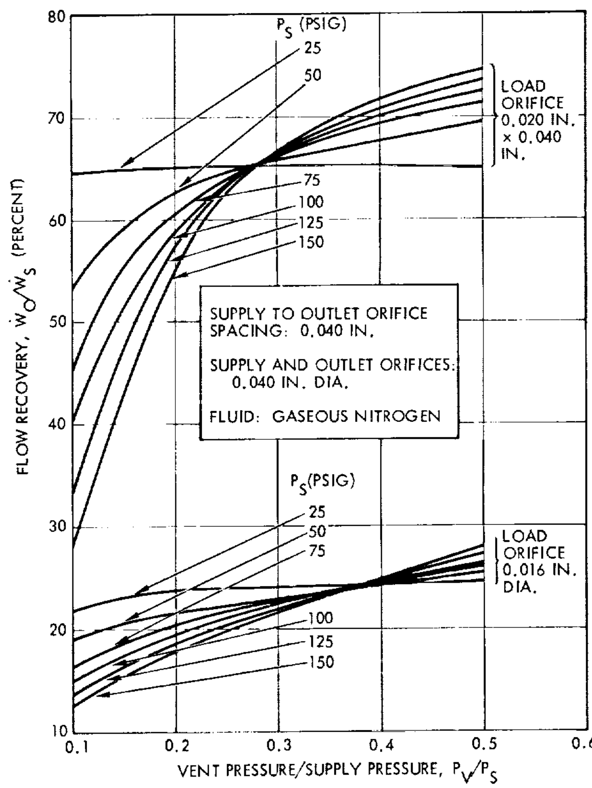


Figure 8-136. Model VJ-1 Vented Jet Output Flow Recovery

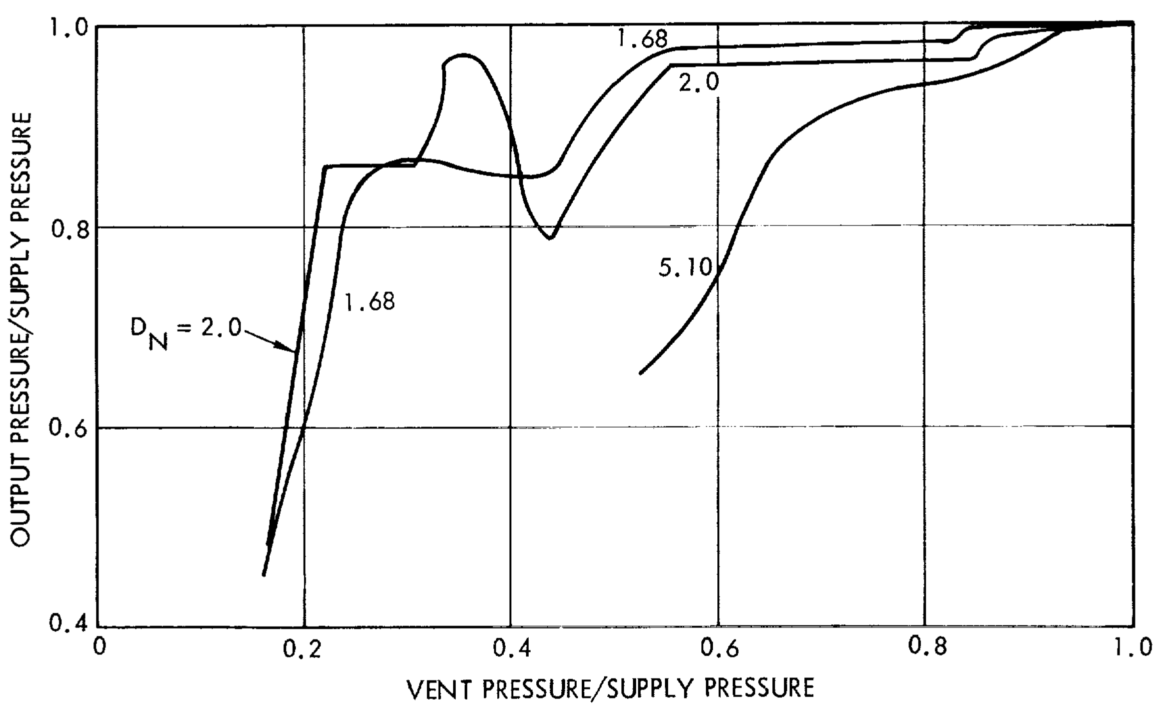


Figure 8-137. Effect of Gap Length on Vented Jet Performance (Courtesy of Bendix Research Laboratories)

Two types of fluid-mechanical boundary conditions are of interest:

1. free surface jets - particularly where a liquid jet emerges into a gaseous media, and
2. submerged jets - where a gaseous or liquid jet emerges into a like medium.

8.7.2.1 Free Surface Jets - An earlier experiment to demonstrate deflection of conducting liquids by coulomb attraction was performed under this program and reported in Reference 20. The apparatus consisted of a cylindrical copper electrode mounted transverse to a liquid jet and about 1 cm from the edge of the jet (Figure 8-138). Water and alcohol were deflected up to 60 degrees by an applied electric field of up to 30,000 volts. However, at specific fluid flow rates there was a critical maximum voltage which resulted in unstable oscillatory jet flow which was attributed to surface tension effects. In this mode, droplets were shed from the stream and accelerated toward the electrode to produce a low resistance path that resulted in arcing. It thus became obvious that this phenomena would only work with a free jet.

Another system using interface polarization forces as a means of modulating a liquid jet issuing in air is shown in Figure 8-139. The electrodes are shaped to produce a strong non-uniform field. The forces on the liquid jet are then due to the surface charges produced by the discontinuities in the dielectric constant and the electric field. It has been shown (Reference 56) that the force and hence the jet deflection is always toward the shaped electrode irrespective of the direction of the field. Again, if the system is submerged the field will dissipate because no interface is present.

The above modulation scheme will not operate with a uniform control field, since no net polarization is produced. However, the jet can be deflected by a uniform field if the jet is charged by a set of emitters (Figure 8-140). The advantage here is that the jet deflection is linear with the applied potential, and also sensitive to the direction of the field. Detailed characteristics are reported in References 57 and 58.

8.7.2.2 Submerged Jets - A liquid operated proportional fluidic amplifier can be controlled by the pressure generated by ion-drag (References 57 and 58). A conceptual design is shown in Figure 8-141, where the control pressure ports are replaced by a set of fine wire mesh control screens. Liquid jet modulation is accomplished by raising the electric potential applied to the control screens above that needed for ionization, so that the transverse momentum imparted by the induced stream of charged particles deflects the jet.

This type device did not operate successfully on air, which was attributed to the fact that the ion-drag pressure generated in air was substantially less than in liquids. In a gas, the charge carriers are electrons instead of ions as in liquids, and the higher mobility of electrons indicates lower frequency of collison with neutral particles with poor momentum transfer the result.

The ion-drag phenomena has been used successfully, however, to trigger the transition from laminar to turbulent conditions in a turbulence amplifier. An ion-drag controlled turbulence amplifier (Figure 8-142) utilizes a set

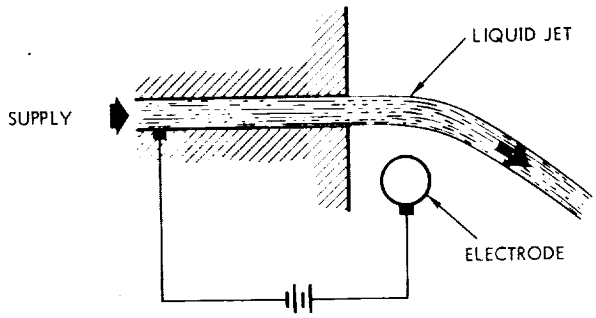


Figure 8-138. Free Jet Deflection by Coulomb Attraction

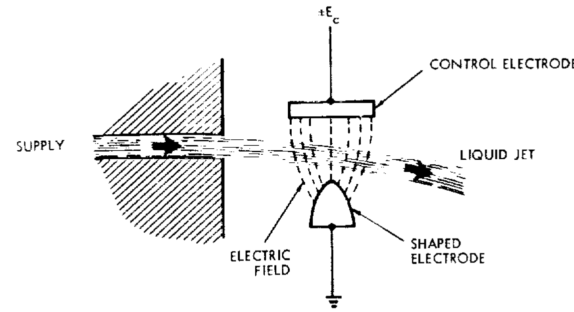


Figure 8-139. Free Jet Modulation by Nonuniform Field

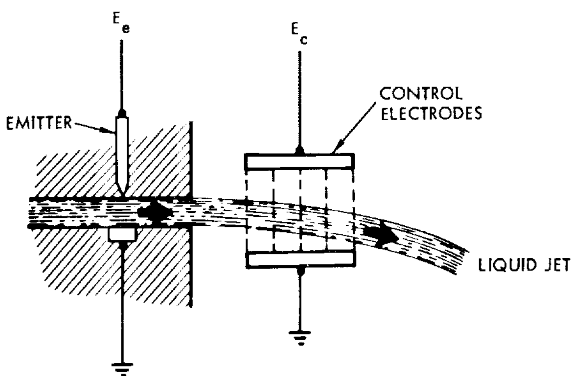


Figure 8-140. Charged Free Jet Deflection by Linear Field

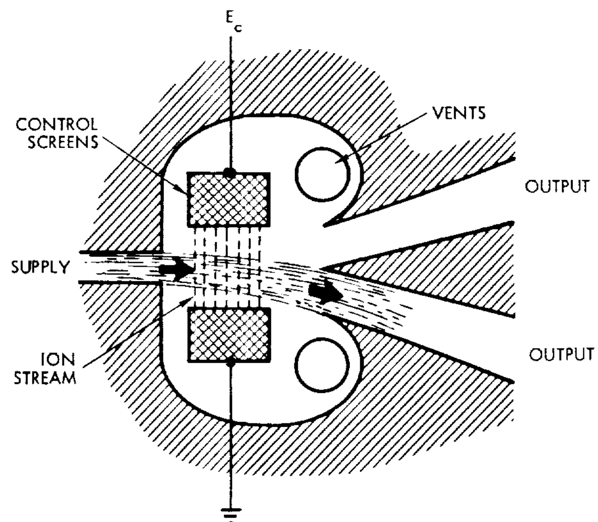


Figure 8-141. Submerged Jet Modulation by Ion-Drag Interaction

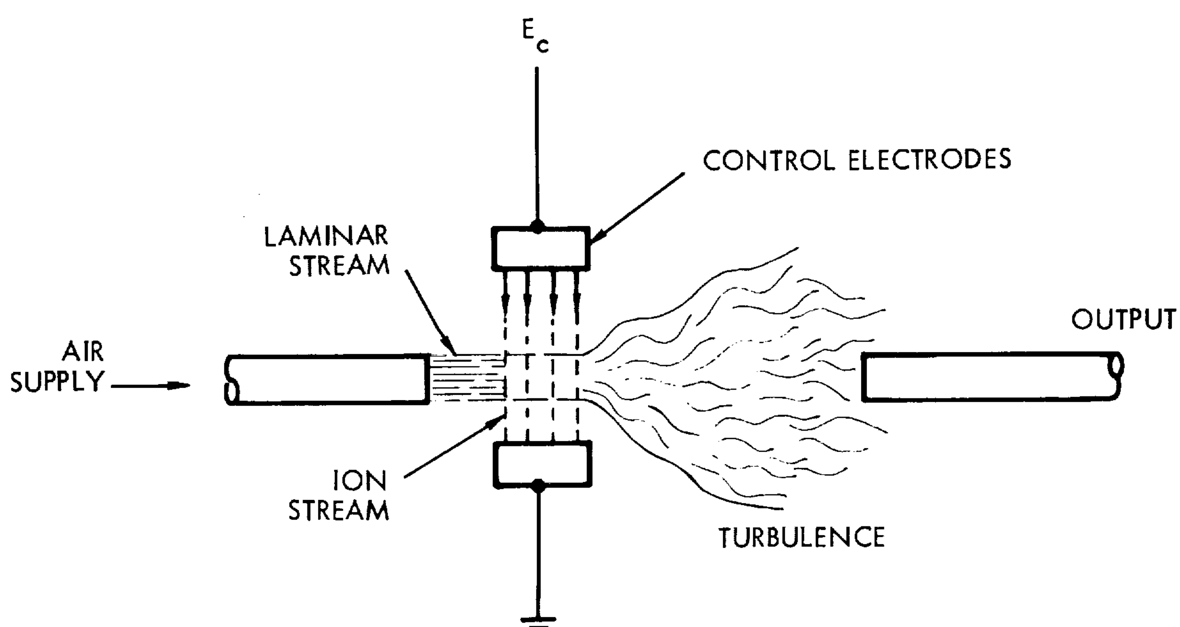


Figure 8-142. Turbulence Amplifier Control by Ion Drag Interaction

of control electrodes in place of the transverse control jets. In this device, an electric potential of sufficient strength causes a continuous corona discharge, so that the ion-drag, or momentum interaction between the charged particles and the supply jet is sufficient to cause the jet to become turbulent. Arcing is undesirable in a useful device because of the excessive power drain with resulting electrode damage. This can be controlled, however, by proper electrode design.

8.7.2.3 Electrical-Fluid Transducers - The electro-fluid modulation effects discussed previously are mostly experimental in nature, but representative of the trend toward eliminating the mechanical interface used in state of the art devices. Other experimental prototypes use heat addition to control the separation point in a boundary layer amplifier (Figure 8-143) and spark discharge to switch a bistable element (Figure 8-144). It is important to note that all of the present prototypes require considerably more electric power than equivalent fluid power for operation. It presently appears that E-F transducer compatibility, i.e., equivalent reliability with a fluidic device, can only be achieved with the higher electrical power drains.

8.7.3 Piezoelectric E-F Transducer

An important property of piezoelectric materials is the deformation that results from the application of an electric field. Of particular interest are the variations of lead zirconate-lead titanate ceramics. Piezoelectric behavior is induced in these materials by a polarizing treatment, since the ceramics are polycrystalline in nature and do not have piezoelectric properties in their original state. A flexing type piezoelectric ceramic element (Bimorph) developed by Clevite is composed of two plates secured together face to face in a particular manner. The advantage of a Bimorph element is that it will bend or displace many times more than a single plate in response to an applied voltage.

Conceptual design, fabrication, and test of an E-F transducer utilizing piezoelectric ceramic elements were completed. These results were analyzed, configurations established, and applications defined.

8.7.3.1 Experimental Procedure - Evaluation of the piezoelectric ceramic type element was accomplished in the balanced flapper nozzle configuration shown in Figure 8-145. The ceramic element is mounted between two sharp edged orifices, so that it essentially replaces the torque motor driven flapper commonly used in the pilot stage of electrohydraulic servovalves. Initial testing was accomplished with a 1 inch diameter by 0.020 inch thick ceramic disk. An alternate configuration was also tested which utilized a 1 inch long by 1/8 inch wide by 0.020 inch thick ceramic beam.

Preliminary calculations were made to predict the output pressure of the test configuration as a function of the ceramic element displacement. Six test points were selected, five with a 30 psig supply pressure and one with a 60 psig supply pressure, as shown in Figure 8-146. At each of the test points the initial test setup was made such that $P_1 = P_2$ when the bimorph disk input voltage was zero. This was accomplished by adjusting the displacement of the sharp-edged orifices relative to the bimorph disk. The output pressure P_2 was not recorded because its magnitude was exactly opposite to P_1, i.e., P_2 decreased the same incremental amount that P_1 increased.

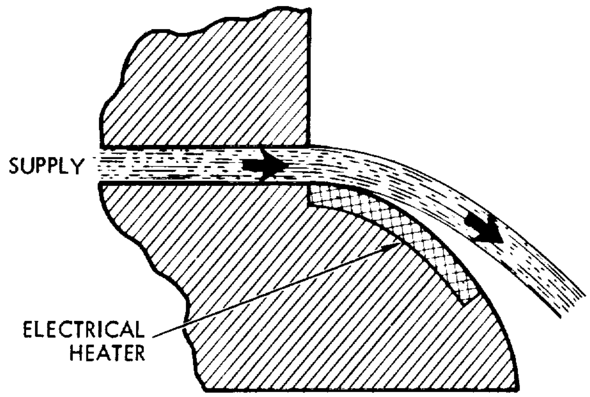


Figure 8-143. Controlled Separation by Heat Addition

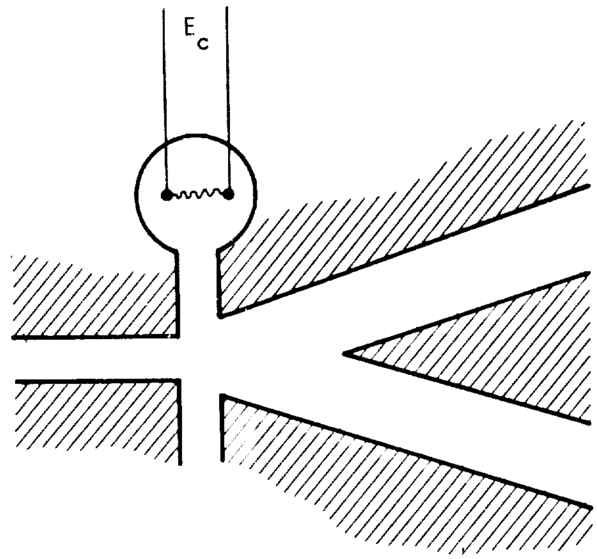


Figure 8-144. Bistable Device Switching by Spark Discharge

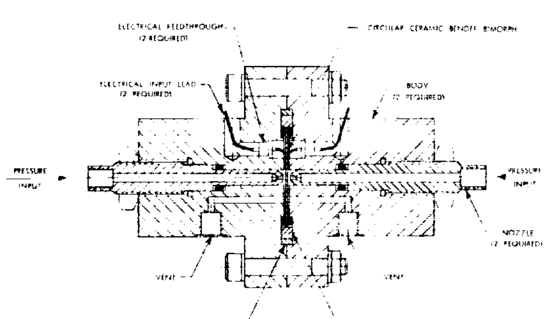


Figure 8-145. Piezoelectric E-F Transducer

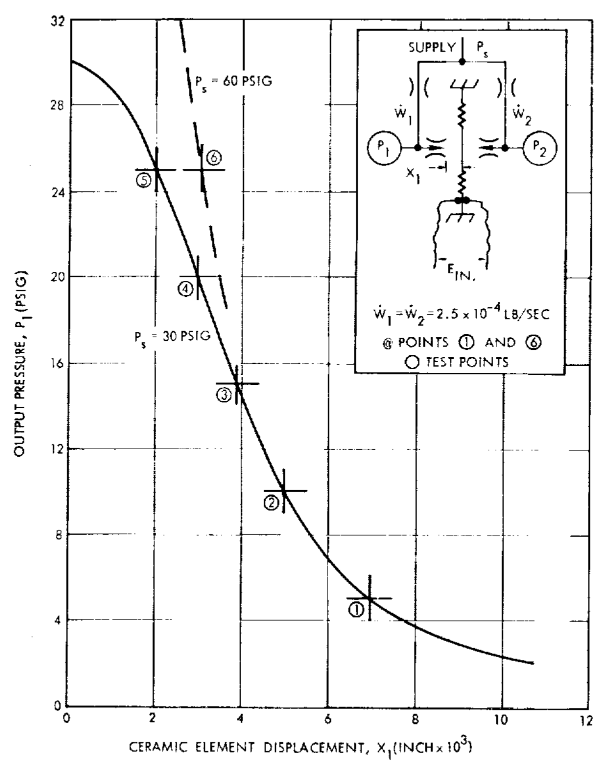


Figure 8-146. Experimental E-F Transducer Test Points and Configuration

8.7.3.2 Steady-State Calibration - Preliminary steady-state testing of the device was completed and the results are shown in Figures 8-147 and 8-148. The data shown in Figure 8-147 was taken with the ceramic disk clampled in a rigid mount and the data shown in Figure 8-148 was taken with the disk clamped in a relatively loose resilient mount. The height of the spacing ring (Figure 8-145) was varied to provide an abnormally high squeeze for the rigid mount and a light squeeze for the resilient mount. In comparing the data, it is obvious that the operation of the device is not noticeably affected by the mount. This is logical, because the maximum deflection of the disk was only about $\pm$ .0005 inch for the voltage levels used. The preliminary results were as would be expected from Figure 8-146, that is, the gain (psi/volt) of the device increases as the output pressure bias level is increased.

Steady-state calibrations were also made with the ceramic beam installed in the test configuration. The insulating ring (Figure 8-145) was notched so that it would accommodate the corners of the beam, and a rigid mount was used. Calibration was performed at test points 2, 4, and 6. These calibrations are shown in Figure 8-149, along with the appropriate disk calibrations for comparison.

The gain (psi/volt) of the disk is much better than the gain of the beam. This would be expected, since the calculated clamped piezoelectric force of the disk was 1.33×10^{-2} newtons/volt and the displacement 4.5×10^{-9} meters/volt as compared to the beam which was 2.45×10^{-3} newtons/volt and 2.4×10^{-9} meters/volt, respectively. In considering point 4, the calculated differential pressure foce on the disk with 50 VDC applied is 9.54×10^{-3} pounds and the clamped piezoelectric force is 0.150 pounds or about 16 times higher. For the beam the pressure force with 50 VDC applied is 4.34×10^{-3} pounds and the clamped piezoelectric force is 2.76×10^{-2} pounds or about 6 times higher. Since the clamped piezoelectric forces are considerably higher than the pressure forces, it would be expected that the gain of the disk versus the beam would be directly related to the ratio of their calculated displacements. This ratio is 4.5×10^{-9} (disk)/2.4×10^{-9} (beam) or about 1.9.

In the actual case (Figure 8-149) the disk/beam displacement ratios at points 2, 4, and 6 are 2, 2.2, and 1.3, respectively. The large variation at point 6 is felt to be due to sonic velocity existing at the annular exit area of the flapper nozzles. Under these conditions the piezoelectric beam element is attracted to the closer flapper nozzle by aspiration, so that the gain of the beam bender is effectively increased. This effect is minimal with the disk because of its extremely high piezoelectric force.

It was concluded that the ceramic disk would be better than the beam for use in the E-F transducer, because of the high piezoelectric force available. In addition, the disk can be used in the driver configuration shown in Figure 8-152. However, in the present configuration, the actual displacement/volt of the disk is severely restricted by the mount; actual displacement is 1×10^{-5} inch/volt, whereas predicted is 2.36×10^{-5} inch/volt. This difference is attributed primarily to the mount. A free disk will deflect the predicted 2.36×10^{-5} inch/volt, whereas the displacement of a clamped disk would be only 25 percent of this figure or about 0.6×10^{-5} inch/volt.

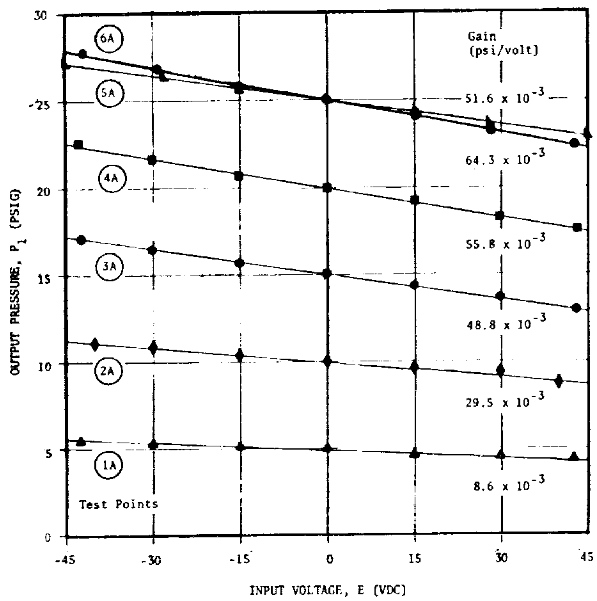


Figure 8-147. Experimental E-F Transducer Steady State Calibration - Rigid Mount

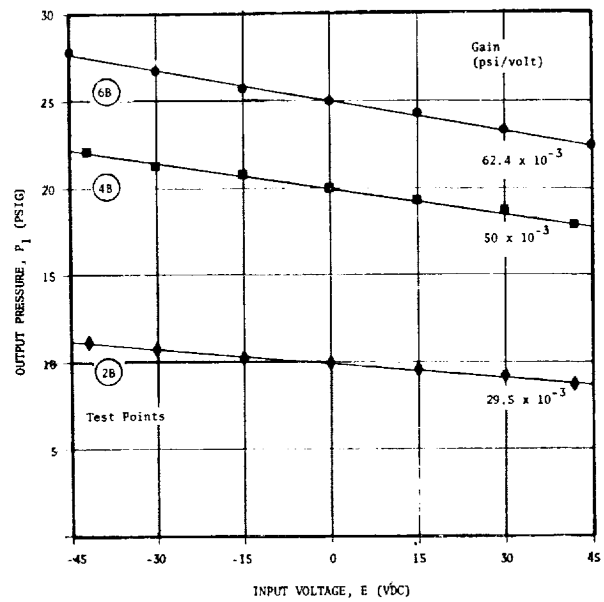


Figure 8-148. Experimental E-F Transducer Steady State Calibration - Resilient Mount.

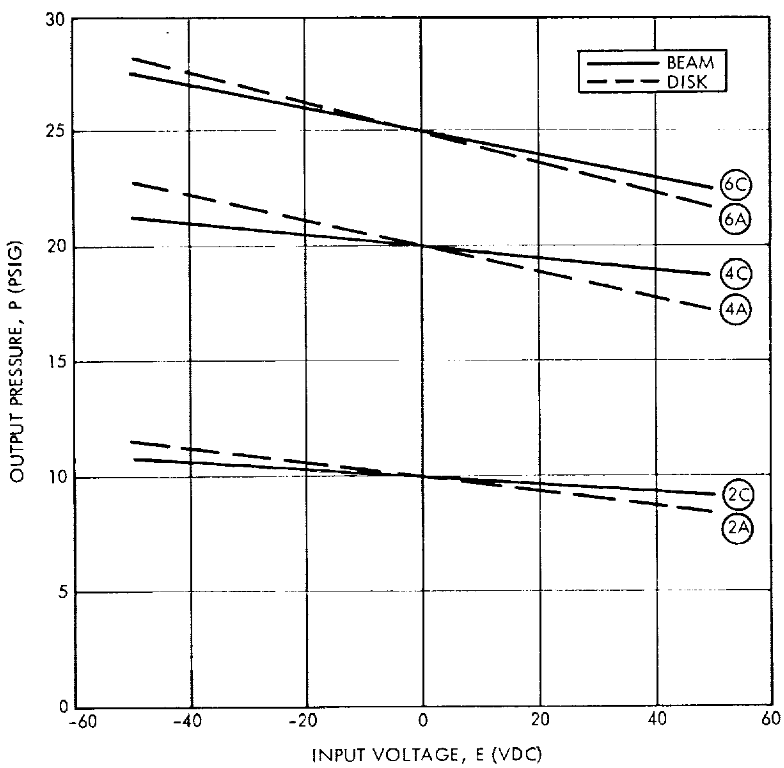


Figure 8-149. Comparison of Disc and Beam E-F Transducer Calibration

Since the present mounting for the disk is apparently close to a clamped design, careful consideration should be given to the mount in future designs.

8.7.3.3 Frequency Characteristics - The frequency characteristics of the piezoelectric E-F transducer were investigated and the results are presented in Reference 11. Data was taken at points 1 through 6 with the disk mounted in the rigid mount, points 2 and 4 with the disk mounted in the resilient mount, and points 2 and 4 with the beam mounted in the rigid mount. These results were compared to the measured first resonant frequency of the ceramic bender elements, which was 3500 hertz for the disk and 1000 hertz for the beam. In general, the cutoff frequencies were much less (<100 hertz) than the resonant frequencies of the ceramic elements. Consequently, a theoretical analysis was undertaken in an attempt to explain the limited experimental bandwidth of the E-F transducer.

An approximate acoustic circuit of the piezoelectric E-F transducer is shown in Figure 8-150. Where the connecting lines between the driver (ceramic disk) and the sensor (pressure transducer diaphragm) are kept as short as possible so as to minimize the acoustic effect. The connecting line will be stiffness or mass controlled depending on the frequency of operation. In this case the supply nozzle is plugged and a no flow condition is assumed in the transmission line.

The viscous resistance, R, and acoustic capacitance, C, of the line were first calculated so as to determine the cutoff frequency of the acoustic R-C circuit. For each line segment (Reference 66), R, is determined from:

$$R = \frac{8\mu\ell}{\pi a^4}$$

where: ℓ = tube length (cm)
a = tube radius (cm)
μ = viscosity (poise)

The total viscous resistance was found to be 5.6 acoustic ohms.

The acoustic capacitance at the end of the transmission line was calculated from:

$$C = \frac{V}{\gamma P}$$

where: V = receiver volume (cm^3)
P = receiver pressure ($dynes/cm^2$)
γ = ratio of specific heat for air

The acoustic capacitance was found to be 1×10^{-7} acoustic farads.

Cutoff frequency is then $f(\text{cutoff}) \approx \frac{1}{2\pi RC} \approx 280{,}000$ hertz, so that the viscous effect can be neglected in calculating the cutoff frequency.

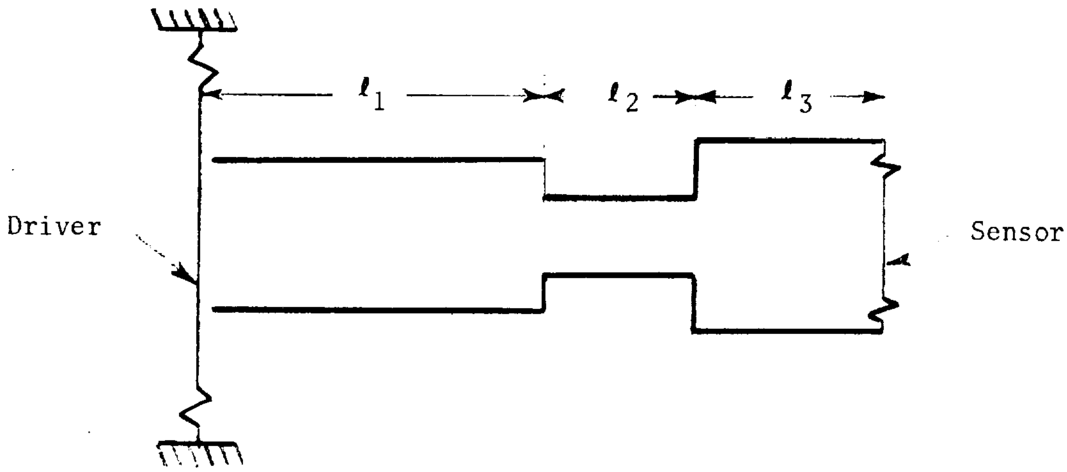


Figure 8-150. Piezoelectric E-F Transucer-Equivalent Acoustic Circuit

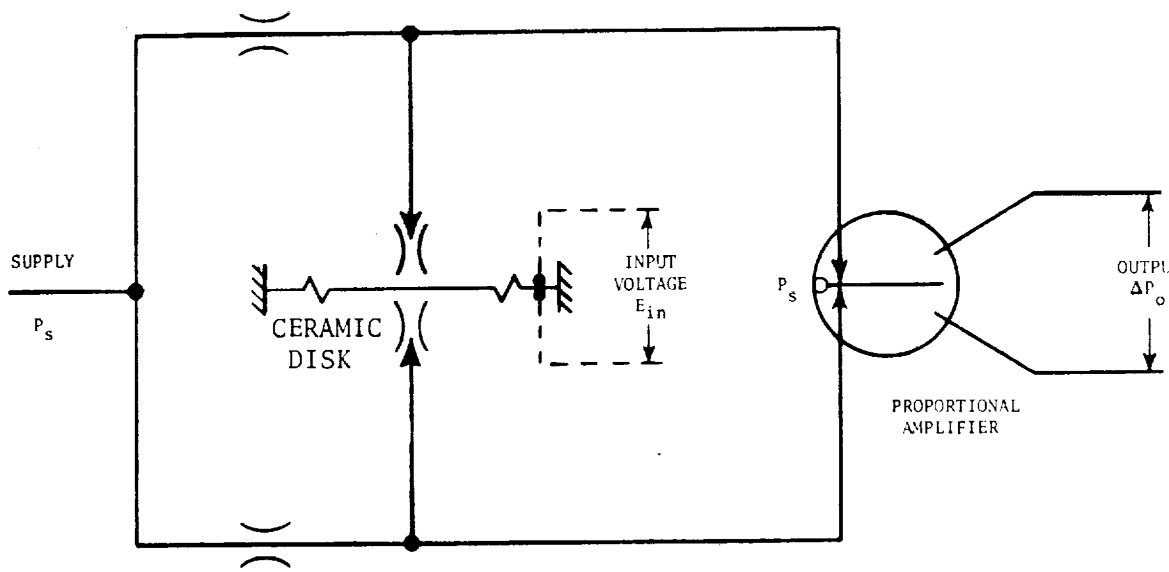


Figure 8-151. Balanced Flapper Nozzle Configuration with Ceramic Disk

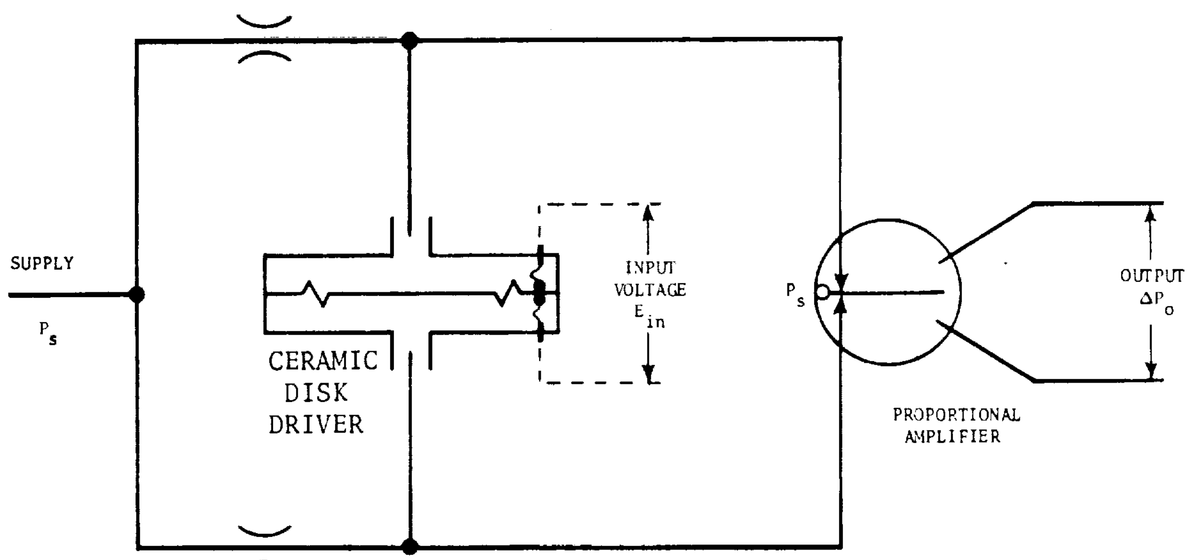


Figure 8-152. Acoustic Driver Configuration With Ceramic Disk

The power transmission coefficient (Reference 67), of the small middle section of the transmission line was then determined from:

$$\alpha_t = \frac{4}{4\cos^2\left(\frac{2\pi f \ell}{C}\right) + \left(\frac{S_1}{S_2} + \frac{S_2}{S_1}\right)^2 \sin^2\left(\frac{2\pi f \ell}{C}\right)}$$

where: f = frequency (hertz)
ℓ = tube length (cm)
C = velocity of sound (cm/sec)
S_1 = transmission line area (cm^2)
S_2 = tube cross sectional area (cm^2)

Neglecting S_2/S_1, α_t was found to be

$$\alpha_t = \frac{4}{4\cos^2\left(\frac{f}{3250}\right) + 1961\sin^2\left(\frac{f}{3250}\right)}$$

The cutoff frequency was then found to be 475 hertz by letting $\alpha_t = 0.5$. This calculated value compares favorably with the experimentally measured cutoff frequency of 350 hertz, which is reduced in the actual case by the abrupt cross sectional changes, viscous dissipation, heat conduction, etc., in the transducer. When flow occurs, the cutoff frequency will be considerably lower since density gradients in the transmission line attenuate the power.

Considering the transmission line with the small cross section center tube removed, measured and calculated resonant frequencies were 1000 hertz and 1930 hertz, respectively. Consequently, the narrow frequency bandwidth of the present E-F transducer is due to the long acoustic transmission line between the driver and the sensor. This device should be capable of a frequency bandwidth of about 1000 hertz, limited only by the physical line length between the driver and the sensor or output port.

8.7.3.4 Applications - A piezoelectric ceramic disk installed in a balanced flapper nozzle configuration is shown in Figure 8-151, where it is used as a pilot stage controlling the inputs to a fluidic proportional amplifier In operation, variations in the input voltage induce axial deflections of the ceramic disk which cause the control differential pressure and consequently the output differential pressure of the proportional amplifier to vary as a direct function of the input voltage level and polarity.

The ceramic disk may also be used as an acoustic driver by totally enclosing it on both sides. A schematic of this configuration is shown in Figure 8-152. A fixed frequency input voltage will result in alternating compression waves applied to the control ports of the fluid amplifier, so that the frequency of the output differential pressure signal is identical to the frequency of the input voltage.

Piezoelectric E-F transducers require no moving parts, except for the ceramic bender which flexes only about $\pm$ 0.002 inch. Potential applications are quite diverse. It will be useful wherever electronic controls are coupled with fluidic controls and it is necessary to maintain system reliability at a level consistent with the fluidic circuit reliability. Specific areas of application will include, but not be limited to:

1. Industrial process and machine tool control
2. Aircraft flight control
3. Shipboard electrohydraulic servo systems
4. Submarine steering and control
5. Long and short range missile guidance and control
6. Spacecraft attitude control

Of particular interest is that the device makes an excellent pilot stage for a servovalve and should also be useful in many other hybrid fluidic control applications.

8.7.4 E-F Digital Output Selector

An E-F transducer was conceived as a direct means of providing a multitude of output signals from a single fluid source. Although it contains a mechanical interface, the E-F Digital Output Selector has numerous application possibilities. These include, (1) control or display functions analogous to the electronic digital computer, (2) attitude control, (3) gain and bias inputs, and (4) presettable counters.

Any fluidic output port in an A by B rectangular matrix of ports can be operated by a single fluid source using a single electrofluidic selector element as shown in Figure 8-153. The electrical control signals designating the output element row and column position may be supplied in either analog or digital form. The electrical position servoactuators adjust the jet attitude corresponding to the separate row and column electrical input signals; for example, the third row and sixth column position in a 10 row by 10 column port matrix would be selected by providing a control input reference signal or address of three for the row position servo and six for the column position servo.

A 10 x 10 outlet port matrix would enable a selection of any number designated port between 0 and 100. The quantity of outlet ports can be increased by use of matrices with the required quantity of outlet ports or more than one matrix may be combined by the use of fluidic logic elements. The electrical row and column position commands may be supplied open or closed loop with respect to the output port selection by a suitable combination of electrical and fluid controls. Figure 8-154 illustrates a typical electrical position control system for the fluid jet row and column position selector.

The row or column position setting creates a corresponding electrical output from an electrical position sensor, for example, an LVDT or potentiometer, which is clamped to the actuator output position mechanism. The output of the position sensor is differentially compared with the corresponding input electrical position command, so that when the difference or error signal is zero, the position actuator motion stops at the commanded position. The slewing rate of the row and column position actuators should be sufficiently rapid to prevent spurious signals from entering the other output ports in

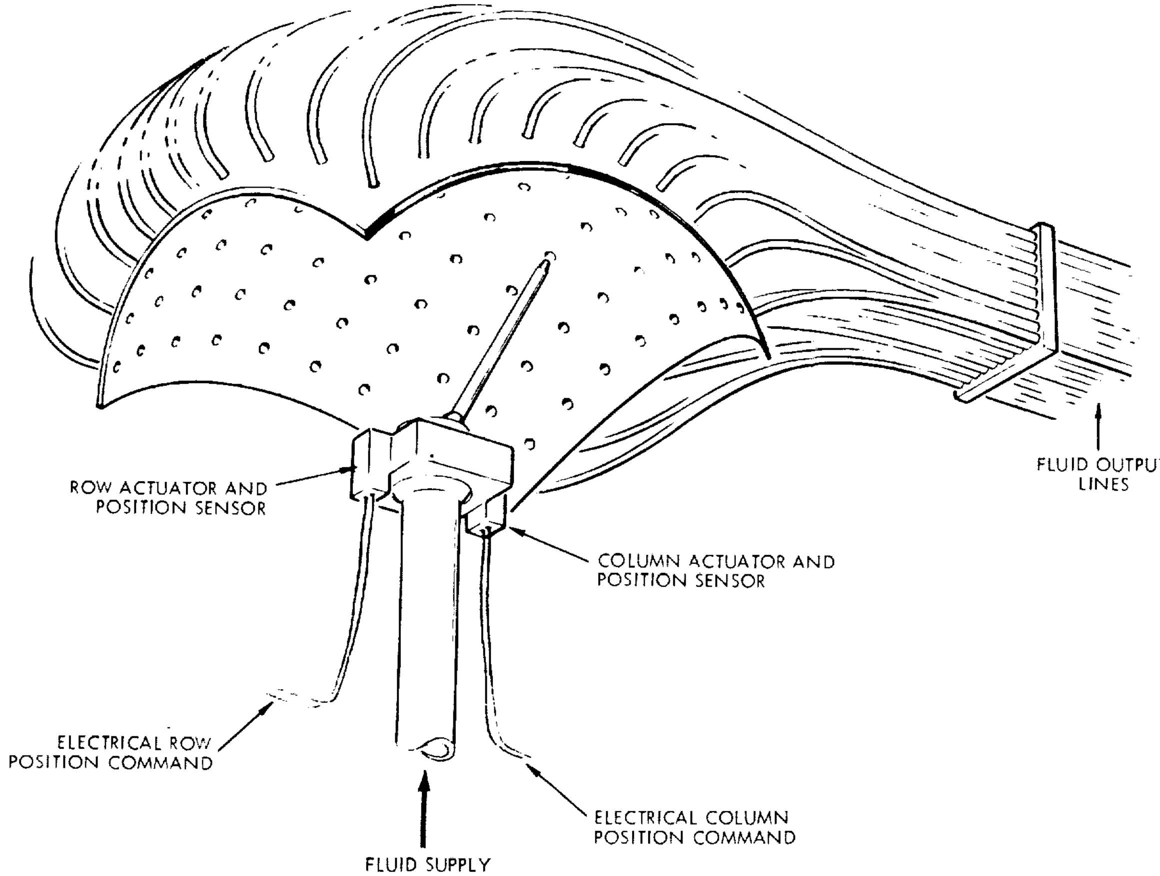


Figure 8-153. E-F Digital Output Selector

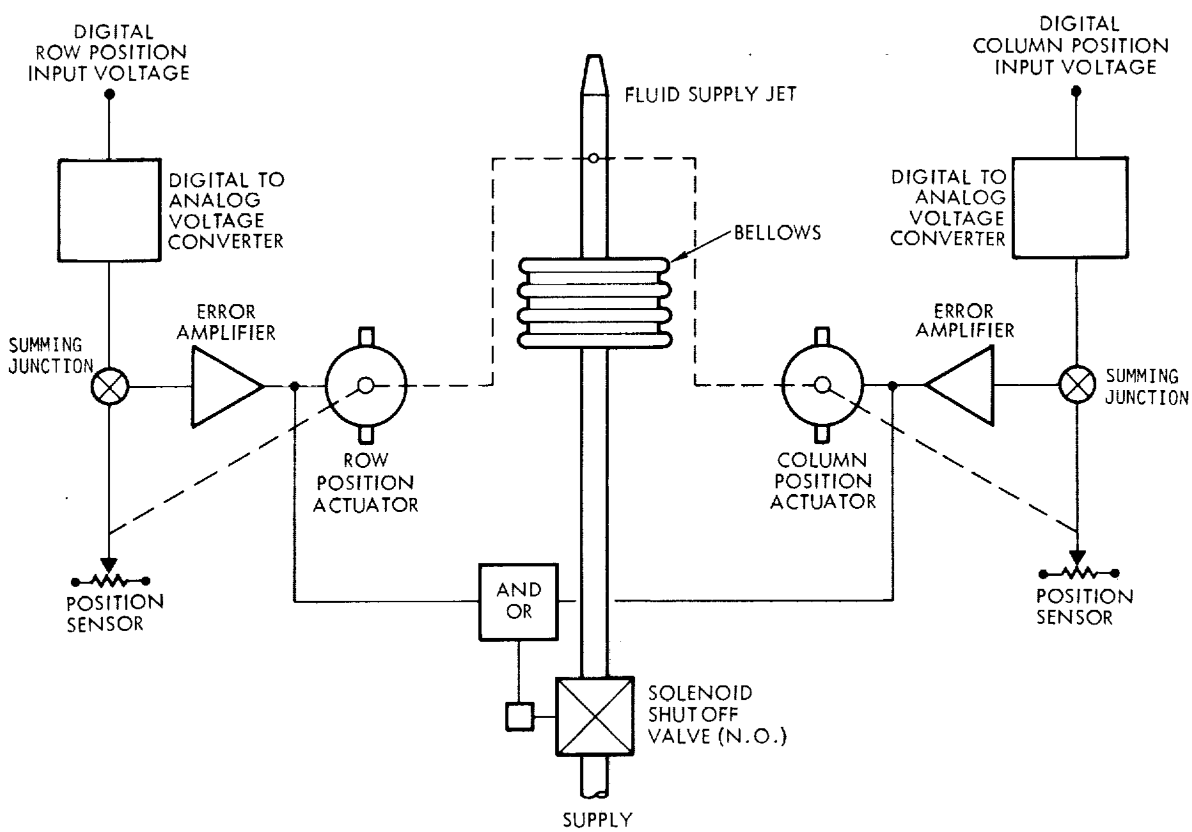


Figure 8-154. E-F Digital Output Selector Servo System

the path of the traversing jet. Interconnecting line lengths or fluidic capacitances are also helpful in smoothing out short duration pulses.

8.7.5 Fluidic Power Supplies

Fluidic controls should provide unique high reliability characteristics for special operating environments of space vehicles. The fluid supply source requires similar high reliability characteristics, if full advantage is to be taken of fluidic circuits. Closed cycle power supplies are felt necessary for spacecraft application, since overboard venting of the working fluid is not practical.

A closed cycle supply must satisfy the modest pressure and flow requirements of fluidic systems, weight much less than expendable pressure supplies, and be consistent with the inherent advantages of fluidic systems. A closed cycle thermodynamic system utilizing available heat sources and spacecraft cold side surface condensers can be used. Capillary pumping of a liquid condensate is useful in installations operating in zero g or with moderate accelerations. This type of supply would avoid the inefficient conversion of electrical energy to fluid energy in cases where the electrical energy was derived from a primary on-board heat source. Waste heat from other spacecraft system operations, radioisotope, or solar heat sources can be used for fluidic power supplies.

8.7.5.1 Closed Cycle Capillary Pumped Power Supply - A concept of a closed cycle power supply for fluidic system applications is shown in Figure 8-155. A small quantity of a two-phase fluid of suitable thermodynamic properties is circulated in the system. The fluid is vaporized in a superheater, passed through a fluidic system load, condensed, pumped by a multi-stage capillary pump, and returned to the superheater. Selection of the working fluid depends on the available heat sources and heat sinks.

Liquid or condensate pumping is provided by capillary pumps (References 68, 69, 70 and 71) which are extensively used for heat transfer applications. The supply pressure increase can be multiplied approximately n times by using n stages of capillary pumps with associated boilers and condensers in series. The boilers are operated from a common heat source and the condensers from a common heat sink. The lowest pressure boiler requires the lowest temperature position on the heat source and sink. Gas or superheated vapor is supplied to the load via a superheater, from the high pressure boiler outlet. The degree of superheat must be sufficient to avoid condensation in the fluidic system, because the presence of condensate could impair the operation of the fluidic elements. The working fluid is returned to the first condenser through a multiple section duct which is designed to support flow, with gas to liquid conversion, as shown in Figure 8-156, without the use of a positive mechanical pump.

8.7.5.2 Working Fluid Requirements - The working fluid must be a gas at near constant temperature during its transit through the fluidic circuits. The working fluid must then be converted to a liquid at the lowest working pressure and temperature available on the spacecraft, i.e., the condenser heat sink. A low heat of vaporization will minimize the thermal energy required for the desired gas flow rate. A wide choice of fluorine, chlorine,

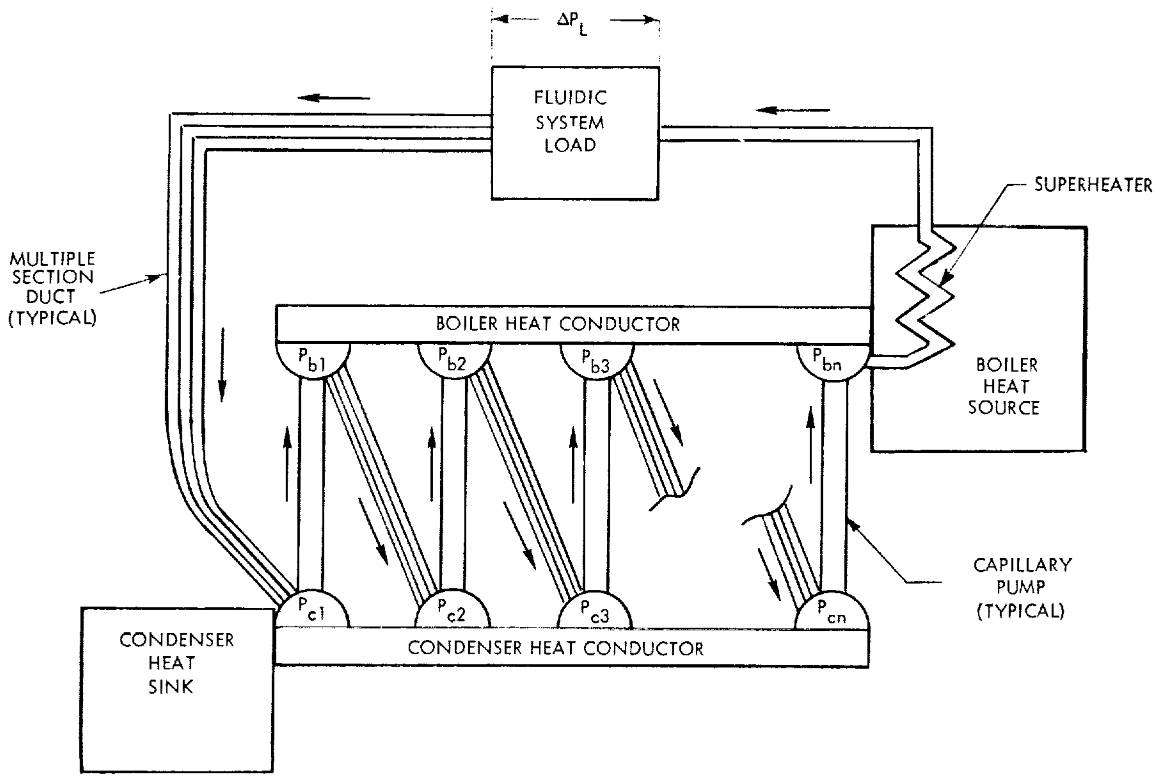


Figure 8-155. Closed Cycle Capillary Pumped Power Supply

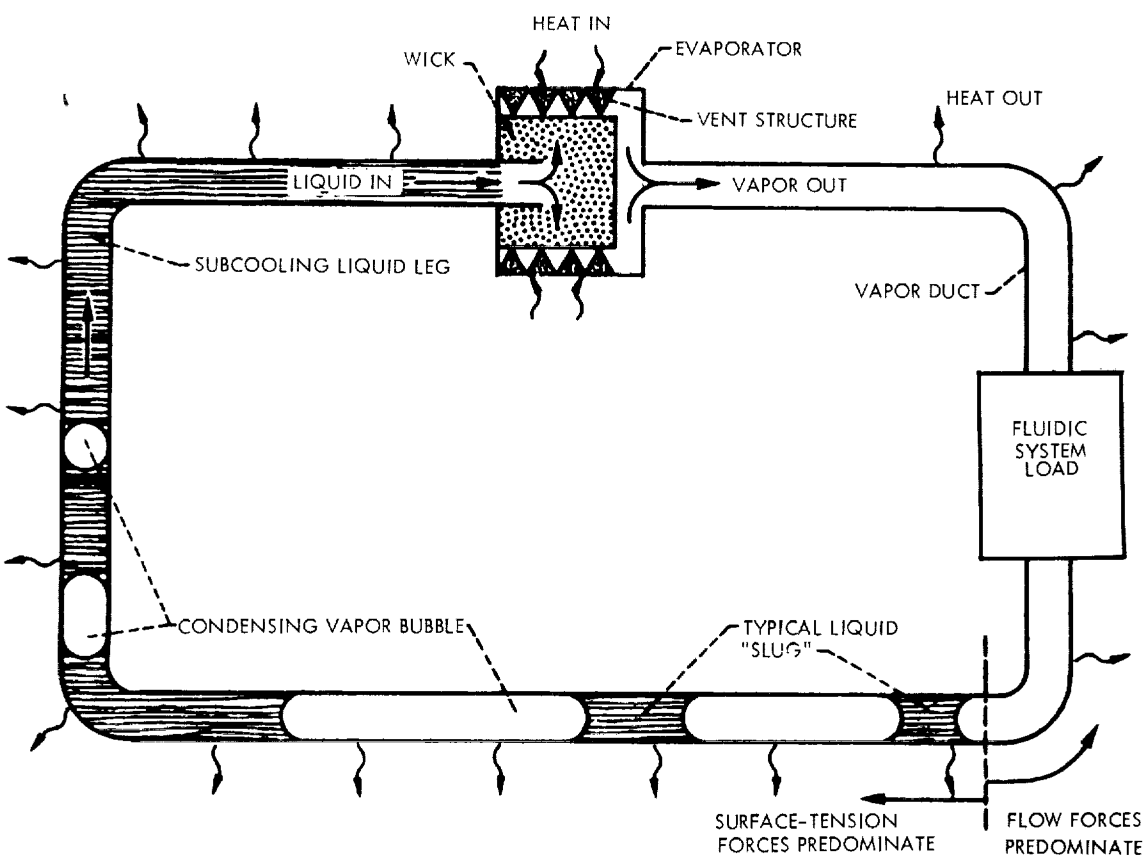


Figure 8-156. Capillary Pumped Heat Transfer Loop

and hydrocarbon compounds as well as the Freons (E. I. duPont deNemours and Co.), and Genetrons (Allied Chemical Co.) are available to satisfy many system thermodynamic requirements.

The thermodynamic properties of many suitable working fluids are available from the manufacturers. The basic heat energy requirements, based on the source and sink temperature, gas volume, and gas pressure requirements, can be estimated on the basis of the thermodynamic cycle and working fluid with an allowance for the estimated system losses. The thermodynamic cyle performance calculations should agree well with actual performance. However, the performance of capillary liquid pumps in thermodynamic gas/liquid cycles is not accurately predictable by use of the available idealized theory, consequently experimental and empirical design information must be used.

8.7.5.3 Fluid and Load Pressure Drop - The pressure drop around the complete loop of a closed cycle fluid flow system must be zero. For the system illustrated in Figure 8-155, the fluidic system differential pressure, ΔP_L, is the sum of the pressure rise of each of the capillary pumps minus the sum of the viscous drops incurred by fluid flow through the capillary pumps, superheater, and interconnecting ducts. This is given by the following:

$$\Delta P_L = \sum_{j=1}^{n} (P_{bj}-P_{cj}) - \sum_{j=1}^{n} (P_{a\ell j}-P_{c\ell j}) - \sum_{j=1}^{n} (P_{bvj}-P_{\ell vj})$$

The first term on the right side of above equation is the pressure rise due to the capillary menisci given by the following equation. The second term in the above equation represents the total pressure drop due to liquid flow in the connecting ducts and capillaries. The capillary pressure drop with high flow demand may be the largest parasitic pressure drop in the liquid system. The last term in the above equation represents the total vapor pressure drop in the system connecting ducts and capillaries excluding the fluidic system load. The capillary vapor pressure drop is usually high and a practical design must minimize this pressure drop.

The capillary system pressure rise is:

$$\sum_{j=1}^{n} (P_{bj}-P_{cj}) = 2 \sum_{j=1}^{n} \sigma_j \left[\frac{\cos\beta_j}{r_{bj}} - \frac{\cos\gamma_j}{r_{cj}}\right]$$

where:
- j = stage number between 1 and n
- σ = surface tension of liquid on wick
- P_b = boiler pressure
- P_c = condenser pressure
- r_b = boiler meniscus radius of curvature
- r_c = condenser meniscus radius of curvature
- β = wetting angle of liquid on boiler wick
- γ = wetting angle of liquid on condenser wick

A large capillary pressure rise requires a small boiler wetting angle, a condenser wetting angle approaching 90°, and a small boiler meniscus radius of curvature. The small boiler capillary radius of curvature dictates a small capillary size which will not accommodate a large capillary flow volume and velocity, hence a compromise between total boiler capillary surface area and capillary pressure drop will define an optimum for any desired flow and pressure requirement. The depth of capillary wick in the boiler and condenser can be a practical minimum to reduce the capillary duct pressure drop.

The pressure drop in the ducts connecting the small pore boiler and condenser capillary boundaries can be minimized by using a larger connecting duct size. The connecting duct size must be sufficiently small to assure liquid entrainment when large bubbles of saturated vapor are present in the duct during the highest acceleration expected. Larger ducts would not give a dependable supply of condensed liquid to the smaller pore boiler capillary, so that the boiler capillary would dry out terminating the capillary pumping of liquid condenstate into the boiler region. Figure 8-156 illustrates the boiler to condenser duct entrainment requirement. The condenser and boiler locations which satisfy spacecraft operation requirements can be connected by long multiple channel ducts which satisfy the liquid-gas-entrainment/acceleration requirement with negligible pressure drops.

The previous equations and the above discussion on pressure drop would suggest an optimum system design for maximum mass flow to the useful load can be obtained by substitution of analytic expressions for viscous gas and liquid pressure drop in the capillary ducts neglecting all other parasitic pressure drops. However, the performance properties of capillaries are not accurately defined by the available theory.

8.7.5.4 Boiler and Condenser Temperature Distribution - The simplified illustration, Figure 8-155 shows multiple boilers coupled to a common heat source and multiple condensers coupled to a common heat sink. To make this arrangement practical, the heat source and sink must be located to obtain the increased boiler and condenser temperature required by the higher pressure boiler and condenser sections. This requirement must be satisfied by connecting the heat source at the high pressure end of the system, and inserting a thermal resistance between each successive boiler to supply connection so as to obtain the desired operating temperature for each boiler at full rated output. The corresponding requirement with a common condenser can be satisfied by connecting the heat sink at the low pressure boiler end with a thermal resistance from the heat sink to each condenser to obtain the desired condenser temperature at full output.

8.7.5.5 Radioisotope Heat Sources - A chemical or nuclear energy heat source may be considered as the primary energy source for the fluidic power supply when waste heat sources or solar radiation are insufficient or intermittent and therefore would not satisfy the operational requirements. Radioactive energy sources are attractive because of the large amount of available energy per unit weight of radioisotope material and their long operating life. The power output density and half life of each basic radioisotope element is a well defined characteristic. However, the rate of energy depletion cannot be arbitrarily controlled to any desired level, since this is defined by the initial energy availability per unit weight and half life. The radioisotope element can be selected for a best fit to the application requirement. The important characteristics for initial selection studies of radioisotope heat sources are given in Table 8-10.

Safety of operating personnel and equipment is an important consideration in the use of large quantities of radioisotopes. The problems and difficulties of safety protection may be relatively simple with sources giving dominantly alpha particle radiation and very difficult for sources giving dominantly gamma, beta, and neutron radiation. Unfortunately, the power density and cost factors favor the gamma and beta radiation sources because many of them are plentiful byproducts of reactor fuel manufacture or reprocessing. The alpha sources are not derived as a byproduct of nuclear reactor fuel manufacture.

Gamma and beta sources need to be isolated or surrounded by extensive heavy shielding, and provision made for the positive containment of all gaseous and solid radioactive materials during mission launch and reentry. Alpha sources must satisfy the containment requirements and nominal radiation shielding requirements since the penetration of alpha particles is very short range except in high vacuum. Any solid or gaseous material can provide effective alpha shielding, hence the isotope containment capsule for alpha sources can readily satisfy the radiation shielding requirements without additional weight. It is likely that beta and gamma radiation source isotopes will not be extensively used for fluidic power supplies because of the severe shielding requirement and possible radiation damage to equipment and personnel.

Two alpha sources are available for heat sources, 210 Po and 238 Pu. The first, 210 Po, provides a very high power density of 141 watts per gram but a relatively short half life of 0.38 years and is therefore suitable for short duration missions. The second, 238 Pu, has a low power density, but its half life of 87.4 years will permit missions exceeding 10 years. The mission life using 238 Pu can be extended to 100 years by utilizing a passive heat flux temperature control developed by RCA and others (References 52 and 72). Although 210 Po is a very hot radioisotope, it presents less of a biological hazard due to accidental inhalation or absorption than 238 Pu. The primary reason is that 210 Po compounds are excreted in the urine and exhibit a half life in the human body of approximately 1 month. The 238 Pu compounds are cumulative in the human body forming insoluble compounds which deposit in the bones, so that the half life in the human body for 238 Pu is 87.4 years.

Containment of the radioisotope heat source and disintegration products can be difficult when high operating temperatures are required. In the case of fluidic system gas pressure supplies the required operating temperature is generally low and encapsulation requirements are easily accomplished. Two basic methods have been considered: (1) complete containment of the isotope and gaseous disintegration products during the operating life and (2) containment of all solid and gaseous radioactive components by the selective venting of accumulative helium excess pressure. Complete containment is accomplished with a totally enclosed capsule which allows sufficient empty volume to accumulate all gaseous disintegration products during the operating life. Vented containment is accomplished by installing a vent and a molecular filter in the capsule which allows only helium permeation to vent and relieve the excess pressure buildup.

Table 8-10. Characteristics of Radioisotopic Heat Sources

		^{60}Co	^{90}Sr	^{106}Ru	^{137}Cs	^{144}Ce	^{147}Pm	^{170}Tm	^{210}Po	^{238}Pu	^{242}Cm	^{244}Cm
1. Watts/Gram (100% Basis)		17.4	0.96	33.1	0.42	25.6	0.33	13.6	141	0.56	120	2.65
2. Half Life, Years		5.24	28	1.0	30	0.78	2.6	0.35	0.38	87.4	0.45	18.1
3. Estimated Isotopic Purity, %		10	55	3.3	35	4.5	95	10	95	80	90	95
4. Compound Form		Metal	$SrTiO_4$	Metal	CsCl	Ce_2O_3	Pm_2O_3	Tm_2O_3	Metal	PuO_2	Cm_2O_3	Cm_2O_3
5. Melting Point of Compound, °C		1480	1910	2310	646	2190	2130	2375	255	2250	1950	1950
6. Active Isotope in Compound, %		10	23	3.3	28	3.8	82	8.8	95	70	82	86
7. Watts/Gram Compound		1.74	0.22	1.1	0.12	1.0	0.27	1.2	134	0.39	98	2.27
8. Density of Compound, g/cm^3, actual or 90% TD		8.8	4.6	12.4	3.2	6.2	6.6	8.0	9.3	10	9	9
9. Power Density, W/cm^3 Compound		15.8	1.01	13.7	0.38	6.2	1.8	9.6	1210	3.9	882	20.4
10. Dimension of capsule for 50 W cm		2.2	4.4	2.3	6.1	2.8	3.9	2.5	2.0	3.8	2.0	2.4
11. Availability		Avail	Avail	Poten Avail	Avail.	Avail	Avail	Avail	Avail.	Avail	Poten Avail	Avail
12. Type of Radiation (Major)*		$\gamma\beta$	β x	$\gamma\beta$ x	$\beta\gamma$ x	$\beta\gamma$ x	β	β	α	α	αn	αn
13. Shielding Required [MeV of significant β or γ]		Heavy (9.5) [1.33γ]	Heavy (6) [2.26β]	Heavy (9) [3.35β]	Heavy (4.6) [1.17β 0.67γ]	Heavy (10.2) [2.98β 2.18γ]	Minor (1) [0.23β]	Moderate (2.5) [0.97β]	Minor (1) [0.8γ]	Minor (0.1) [0.04γ]	Minor (0.4) [0.04γ]	Moderate (2) [0.04γ]
14. Biological Hazard, MPC, AIR, Continuous Exposure	Ci/m^3	3×10^{-9}	10^{-10}	2×10^{-9}	5×10^{-9}	2×10^{-9}	2×10^{-8}	10^{-8}	7×10^{-11}	7×10^{-13}	4×10^{-11}	3×10^{-12}
	W/m^3	4.6×10^{-11}	6.8×10^{-13}	2×10^{-11}	2.4×10^{-11}	1.6×10^{-11}	7.2×10^{-12}	2.3×10^{-11}	2.2×10^{-12}	2.3×10^{-14}	1.4×10^{-12}	10^{-11}
	g/m^3	2.7×10^{-12}	7×10^{-13}	5.9×10^{-13}	5.8×10^{-11}	6.3×10^{-13}	2.2×10^{-11}	1.7×10^{-12}	1.6×10^{-14}	4.1×10^{-14}	1.2×10^{-14}	3.7×10^{-11}
15. Estimated Future Price $/g(Pure) [Present price]		280 [452]	20 [29]	120	6.5 [10.9]	50 [477]	75 [186]	136	2800	300	2000	170
16. Estimated Future Price, $/W		16	21	5	15.5	2	220	10	20	540	17	64
17. Curies/Gram (100% Basis)		1130	142	3394	87	3180	928	6048	4500	17	3320	81
18. Curies/Watt		65	148	102	207	124	2788	445	32	30	28	29
19. Total kWh_t/initial gram for (yr) mission		575 (5)	74 (10)	210 (1)	33 (10)	150 (1)	6 (3)	33 (0.4)	350 (0.4)	47 (10)	310 (0.4)	190 (10)
20. Minim Cost, $/$kWh_e$ for (yr) mission		15 (5)	6 (10)	23 (1)	4 (10)	11 (1)	350 (3)	125 (0.4)	235 (0.4)	138 (10)	180 (0.4)	22 (10)
21. Spontaneous Fission Half-Life, Yr		--	--	--	--	--	--	--	--	4.9×10^{10}	7.2×10^{6}	1.4×10^{7}
22. Estimated Recovery from Power Reactor Fuels; g/metric ton at 25,000 MWd/ton		--	360	53	835	89	60 (aged)	--	--	(345 Np)	--	9 (200 Pu Recycle)
23. Production in Power Reactors Kg/1000 MWY_e		--	16	2.3	36	3.8	3.6 (aged)	--	--	(15 Np)	--	0.4 (9 Pu Recycle)
24. Availability in 1980, kW_t		MWs	1200	11,000	1200	8400	53	MWs	MWs	250(l)	--	93 156(m)

8.7.6 Venturi Sump

One of the problems preventing the use of fluidics in spacecraft propulsion controls is the requirement for venting the working fluid in state of the art liquid systems. A venturi sump has been developed which is a practical solution to the venting requirement, in that working fluid may be bypassed from the mainstream and returned via the venturi sump. The venturi sump also provides a constant pressure reference when cavitating which is useful in regulation systems.

A total of 454 steady state operating points were documented to determine the operating characteristics of the venturi sump. A fluidic system was successfully operated while venting to the sump.

8.7.6.1 Venturi Sump Configuration - An existing cavitating venturi with pintle was modified for use in the evaluation of the venturi sump concept. The original venturi pintle was made with an integral piston actuator to axial adjust the pintle position. For the venturi sump (Figure 8-157) the pintle was adapted by cutting off the end, boring out the center of the pintle, drilling flow paths from the outside of the piston to the center, and adding a constant diameter pintle extension with eight equally spaced return orifices. The downstream valve body section was fabricated in Lucite to permit visual observation of the cavitation region.

The venturi sump test configuration (Figures 8-158, 8-159, and 8-160) allowed the axial adjustment of the pintle so that the return orifice could be located anywhere between about 1/8 inch upstream and 3/8 inch downstream of the throat (minimum area point) without varying the throat area. The pintle was adjusted and clamped externally. The return orifices were also used to measure the cavitation bubble pressure when the cavitation characteristics of the venturi sump was documented.

8.7.6.2 Test Setups - The test setup for the steady state testing of the venturi sump is shown in Figures 8-161 and 8-162. A fluidic control demonstration was also performed in the test setup shown in Figures 8-163 and 8-164. The test instrumentation and nomenclature is defined in Table 8-11.

8.7.6.3 Cavitating Flow Characteristic - Tests were performed with water to establish the cavitation performance of the venturi sump. A one-half inch axial adjustment of the pintle was possible, so that the return orifices in the sump could be located anywhere between about 1/8 inch upstream and 3/8 inch downstream of the throat without varying the throat area. Cavitation characteristic was investigated at each of five positions and at supply pressure of 100, 200, and 400 psia, so as to determine the effect of pintle and body centerline variations on performance. The test points were:

1. Full in - 1/8 inch upstream of throat
2. 25% in - at the throat (minimum area point)
3. 50% in - 1/8 inch downstream of throat
4. 75% in - 1/4 inch downstream of throat
5. 100% in - 3/8 inch downstream of throat

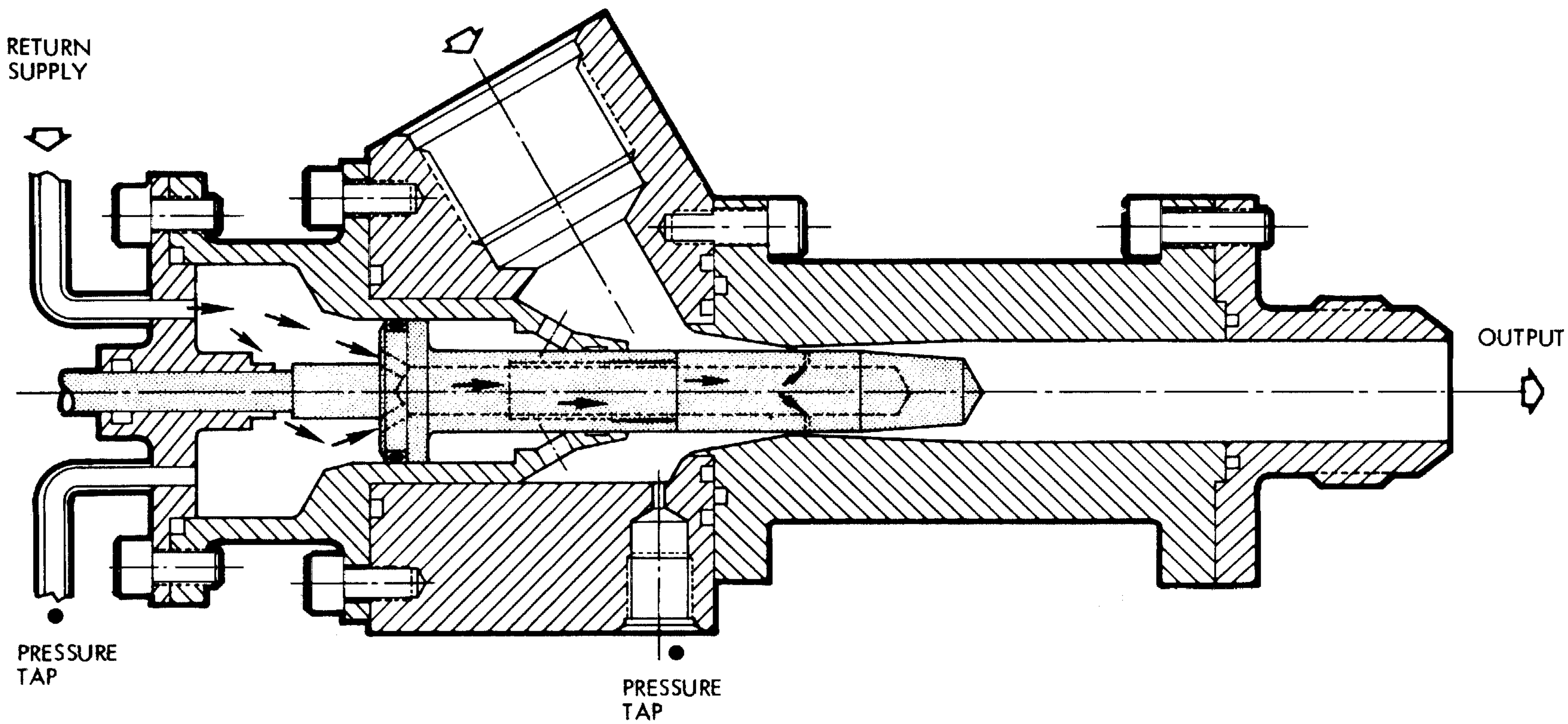


Figure 8-157. Venturi Sump Configuration

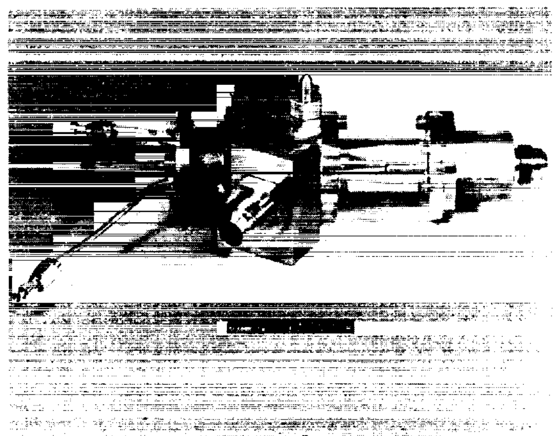


Figure 8-158. Venturi Sump Assembly

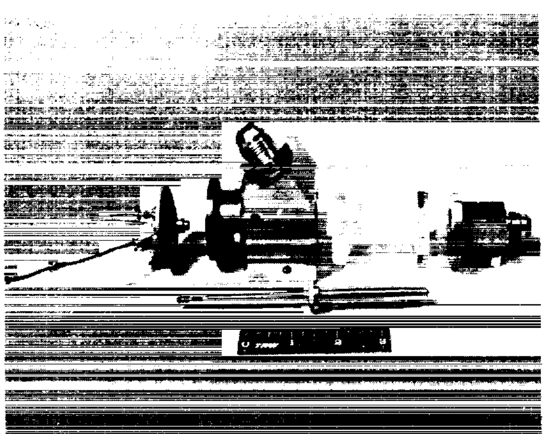


Figure 8-159. Venturi Sump Component Parts

Figure 8-160. Venturi Sump Return Orifices in Pintle

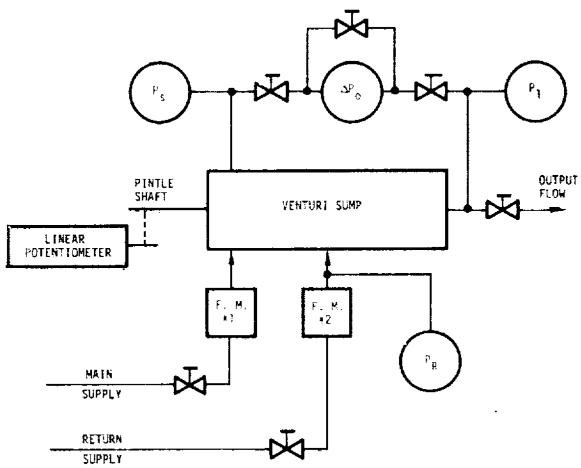


Figure 8-161. Venturi Sump Test Set-up and Instrumentation

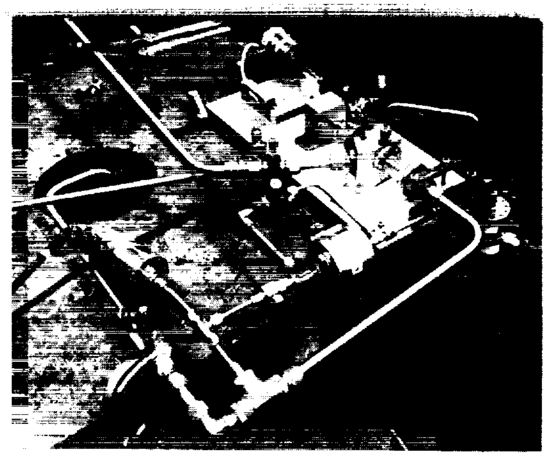


Figure 8-162. Venturi Sump Test Setup

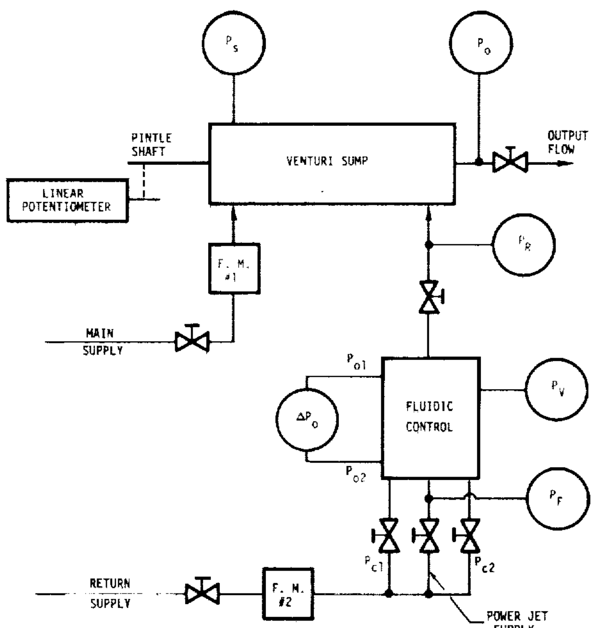


Figure 8-163. Fluidic Control Demonstration Test Setup

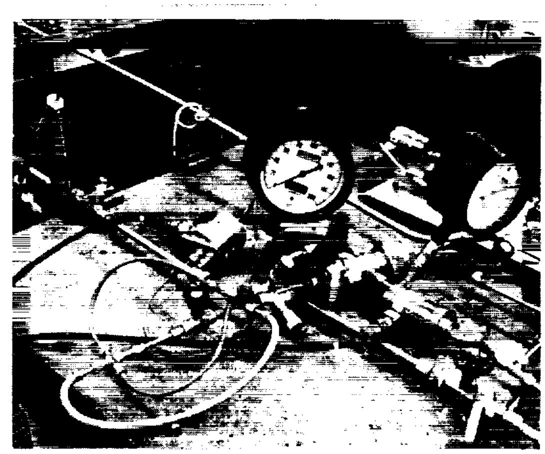


Figure 8-164. Fluidic Control Demonstration Test Setup

Table 8-11. Venturi Sump Test Instrumentation

Parameter	Nomenclature	Range	Full Scale Accuracy (%)
Main Supply Flow	F.M. #1	4.5 to .5 gpm	$\pm$ 1
Return Supply Flow	F.M. #2	0.3 to .03 gpm	$\pm$ 1
Main Supply Pressure	P_S (high)	400 psig	$\pm$ .25
Main Supply Pressure	P_S (low)	60 psig	$\pm$ .1
Output Pressure	P_O	400 psig	$\pm$ .25
Supply-Output Differential Pressure	ΔP_1 (high)	50 psid	$\pm$ .5
Supply-Output Differential Pressure	ΔP_1 (low)	10 psid	$\pm$ .5
Return Pressure	P_R (high)	100 psig	$\pm$ .1
Return Pressure	P_R (low)	30 psig	$\pm$ .1
Return Pressure	P_R (vacuum)	14.7 to 0.3 psia	$\pm$ .25
Fluidic Amplifier Output Differential Pressure	ΔP_O	15 psid	$\pm$ 1
Fluidic Amplifier Vent Pressure	P_V	100 psig	$\pm$ 1
Fluidic Amplifier Supply Pressure	P_F	100 psig	$\pm$ 1
Fluidic Amplifier Control Pressures	P_{c1}, P_{c2}	-	-
Fluidic Amplifier Output Pressures	P_{o1}, P_{o2}	-	-

The cavitation performance of the venturi sump is depicted in Figures 8-165 through 8-168. Although not optimum, the cavitation limits are more than adequate for the test model of the venturi. The limits very from about 62 percent at 100 psia supply pressure to about 81 percent at 400 psia supply pressure. The limit is defined as maximum output pressure at which cavitation will occur in terms of the supply pressure (i.e., $P_o/P_s \times 100$).

These limits hold for all the pintle positions except when the return orifices are at the throat (25 percent in) as shown in Figure 8-166. In this case, the presence of the return orifices at the throat causes turbulence which tends to slightly reduce the pressure recovery and hence the cavitation limit.

The venturi sump in several cavitation modes is shown in Figure 8-169 for supply pressures of 100 psia and 400 psia and various output pressures.

Measurements were also made of the cavitation bubble pressure, by utilizing the return orifices as a pressure tap. It was noted that the measured cavitation bubble pressure was constant over a wide range of back pressures as long as the return orifices were covered by the cavitation bubble.

8.7.6.4 Return Flow Capability - Prior to determining the return flow capability of the venturi sump, the return orifices were calibrated with both water and gaseous nitrogen (Figures 8-170 and 8-171). Since it wasn't possible to measure the cavitation bubble pressure while the return supply was flowing, the return flow capability of the venturi sump with water supply and return flows was judged on the basis of how well the return flow in cavitation compared to the return orifice flow calibration. That is, if the test points fell on the return orifice flow calibration line, the return flow did not change the cavitation bubble pressure (presuming the bubble pressure was near zero psia).

The return flow capability of the venturi sump when in cavitation is shown in Figures 8-172 through 8-175. It can be seen that the best fits relative to the return orifice flow calibration occur with the pintle 37-1/2 percent in and 50 percent in. Excellent return flow capability at constant pressure was exhibited at the 37-1/2 percent in pintle position (15 percent with a 100 psia supply) and the 50 percent in pintle position (13.5 percent with a 100 psia supply and 9.5 percent with a 200 psia supply). These results also occurred over a wide range of back pressure. With the pintle 25 percent in (minimum area point), the return flow sees a higher pressure because the cavitation bubble forms further downstream. With the pintle 75 percent in and particularly 100 percent in, the return orifices are too far downstream so that the cavitation bubble only covers the orifices when the sump is in deep cavitation. The venturi sump in cavitation with the pintle 37-1/2 percent in and for various percentages of return flow and at several supply pressures and output pressure levels is shown in Figures 8-176 through 8-179.

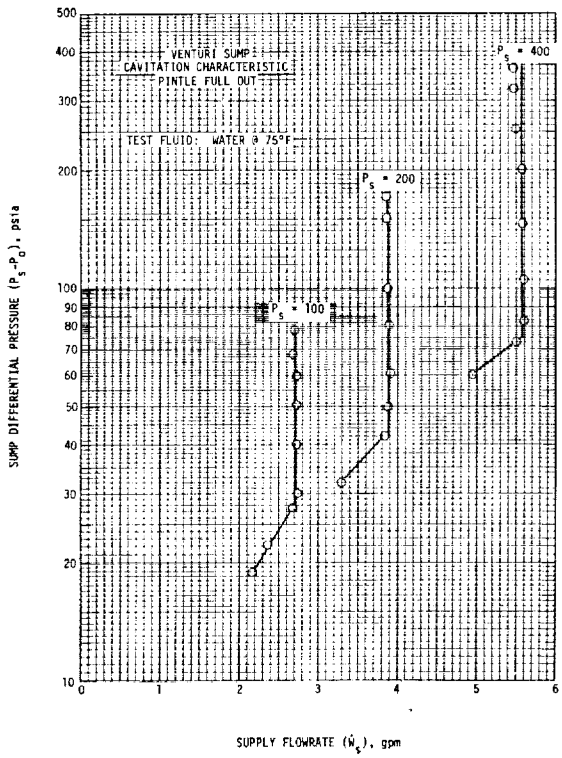


Figure 8-165

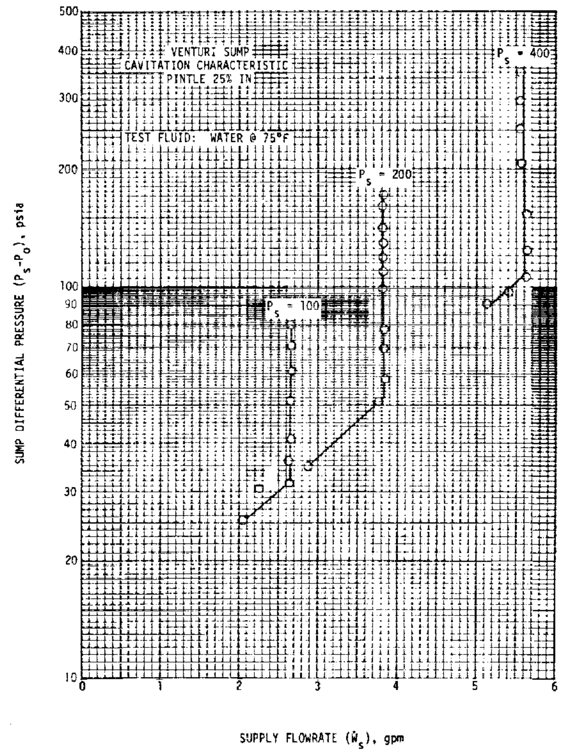


Figure 8-166

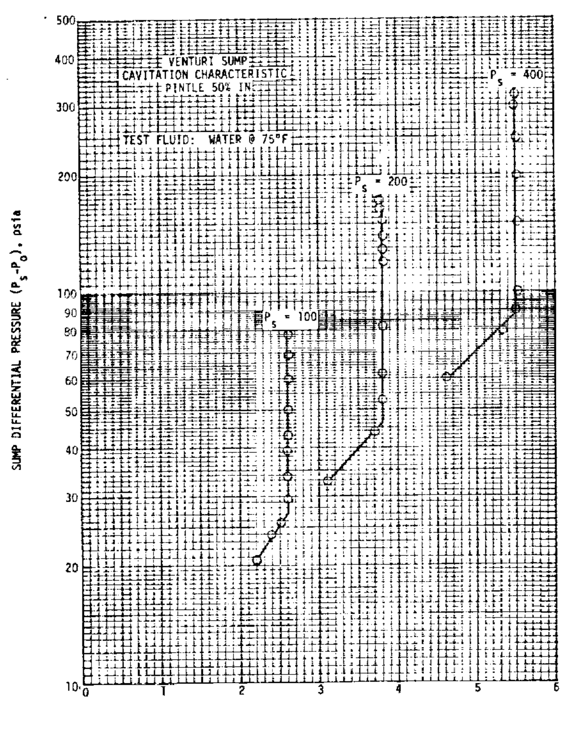


Figure 8-167

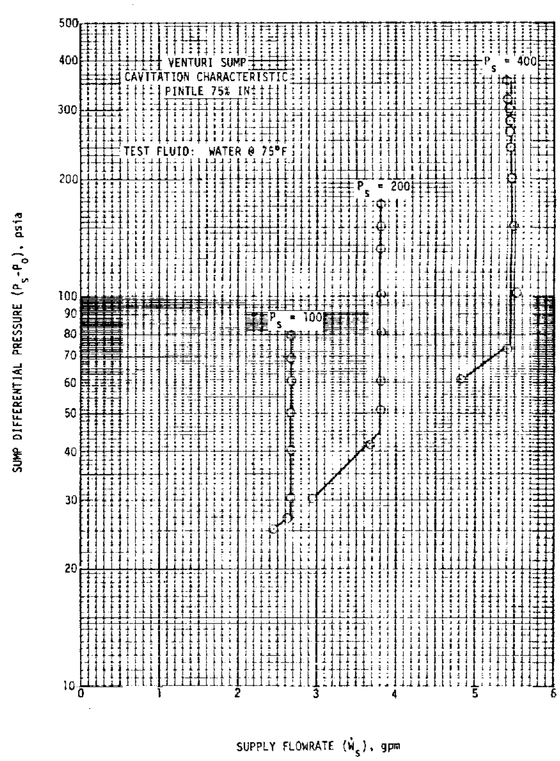


Figure 8-168

Figure 8-169. Venturi Sump in Cavitation (with Water @ 75°F)

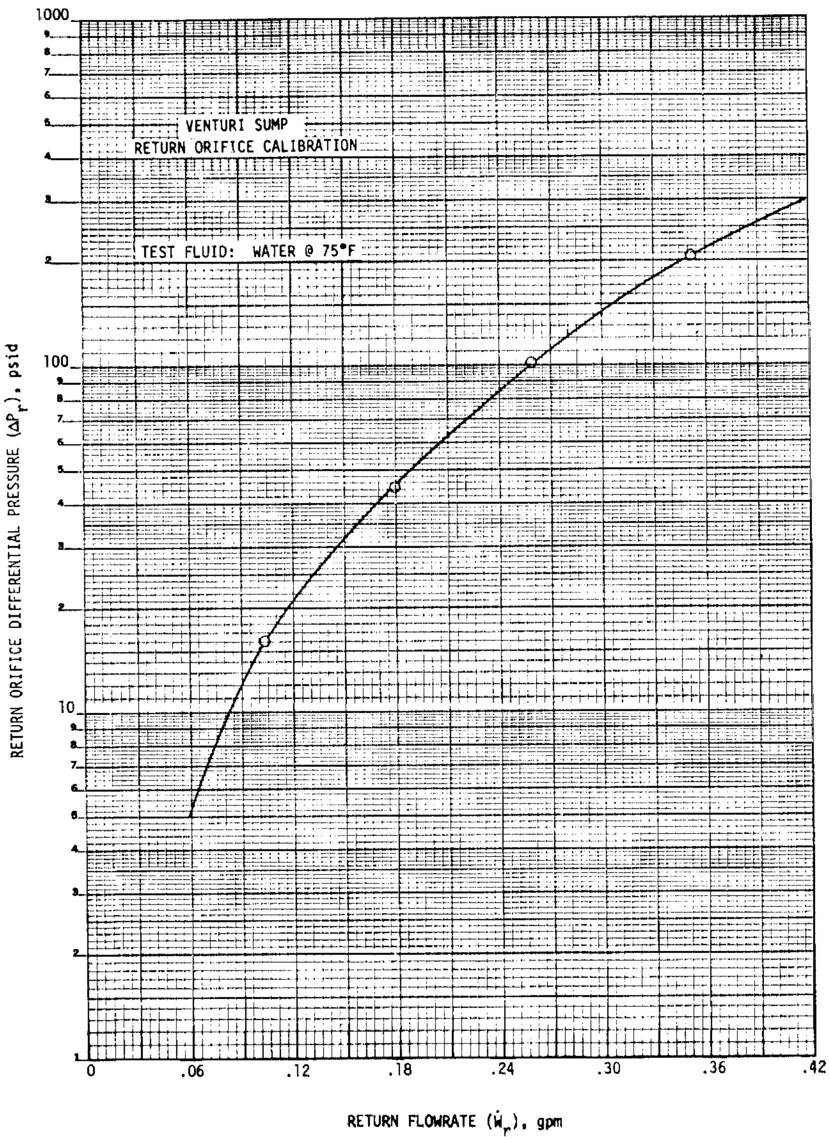


Figure 8-170

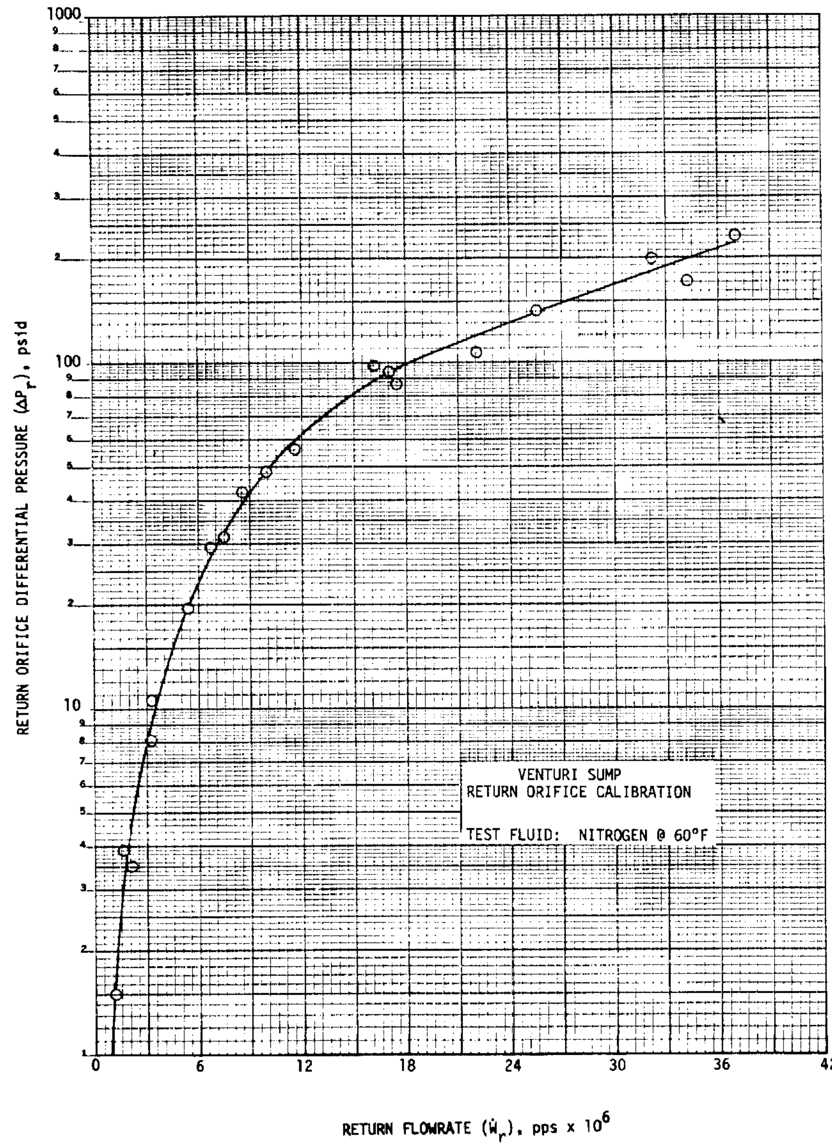


Figure 8-171

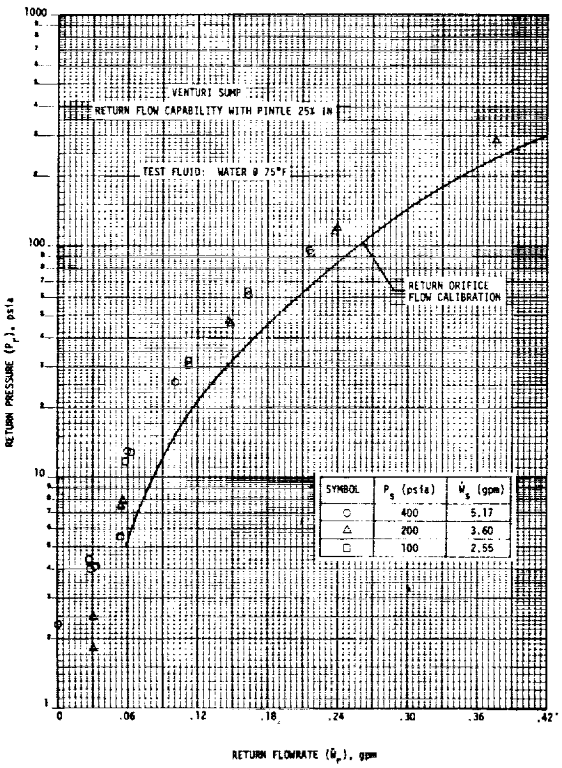


Figure 8-172

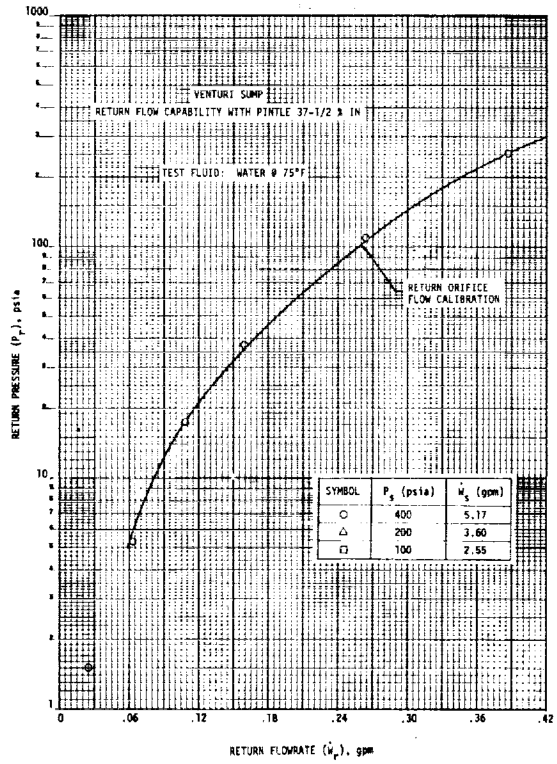


Figure 8-173

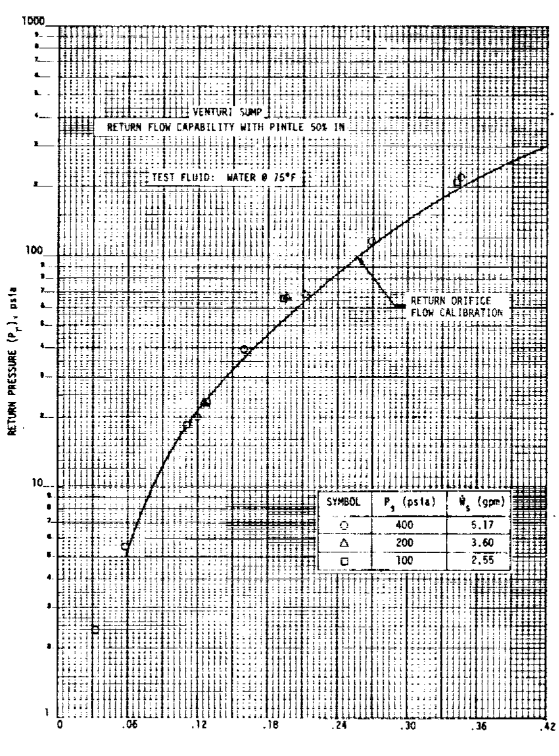


Figure 8-174

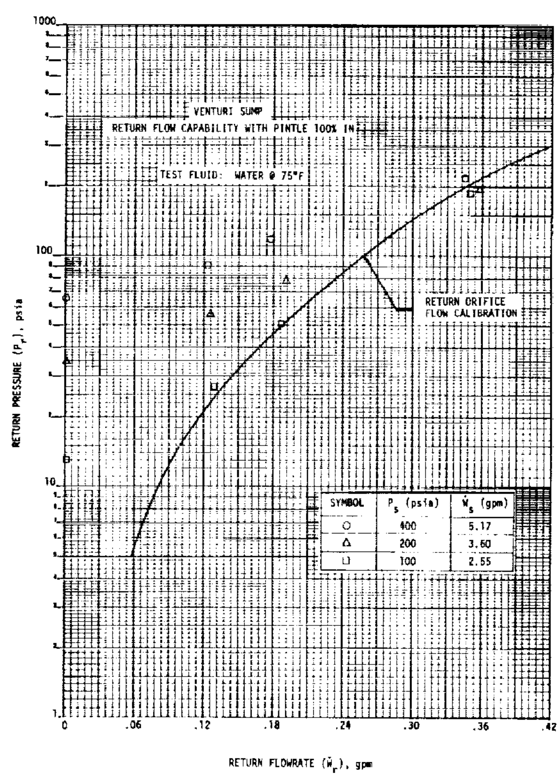


Figure 8-175

SUPPLY AND RETURN FLUID WATER @ 75°F

Figure 8-176. Return Flow in Venturi Sump (Pintle 37-1/2% in, Supply 400 psia 5 gpm, P_o/P_s= 0.2)

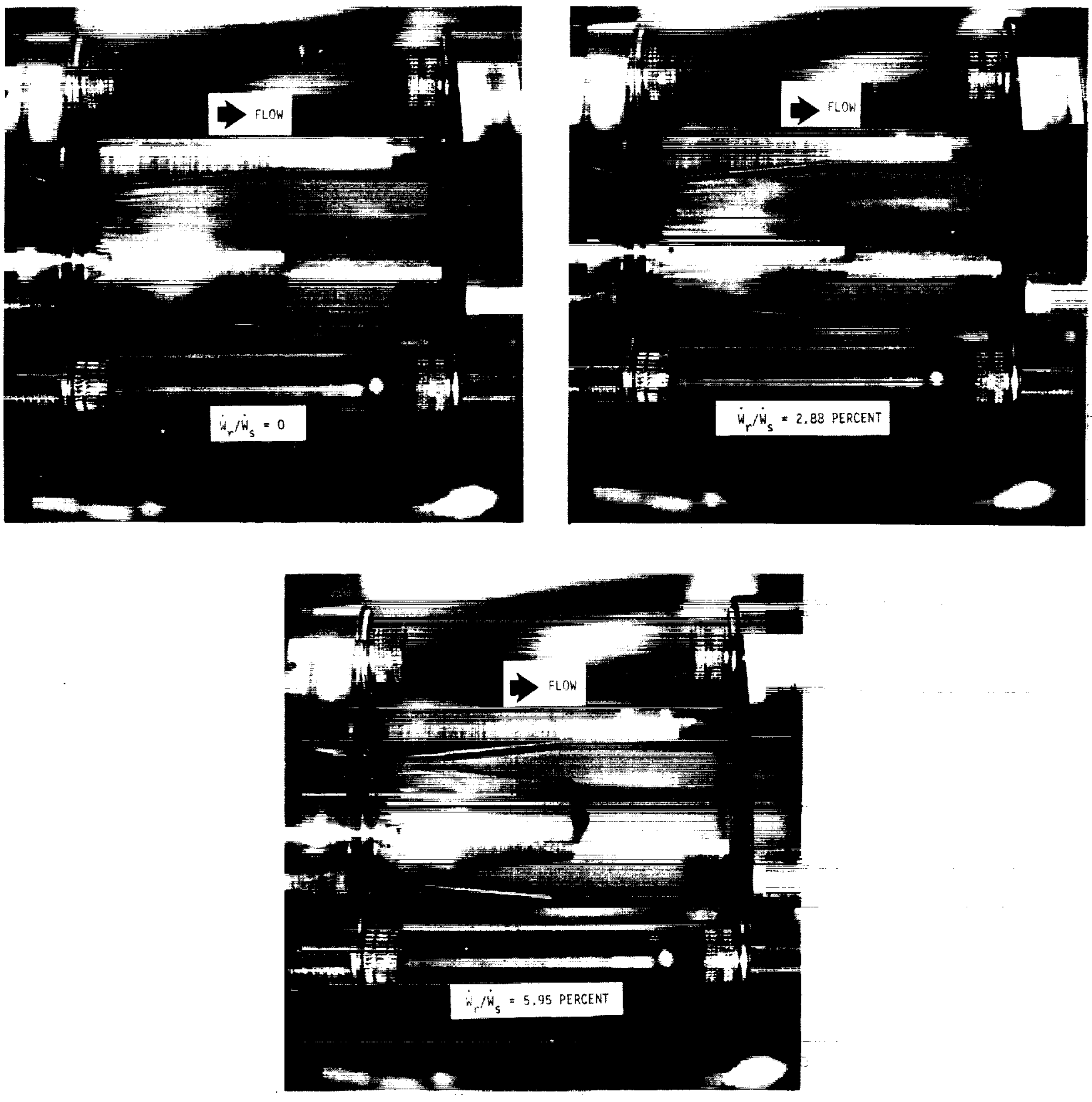


Figure 8-177. Return Flow in Venturi Sump (Pintle 37-1/2% in, Supply 200 psia 3.47 gpm, P_o/P_s = 0.132)

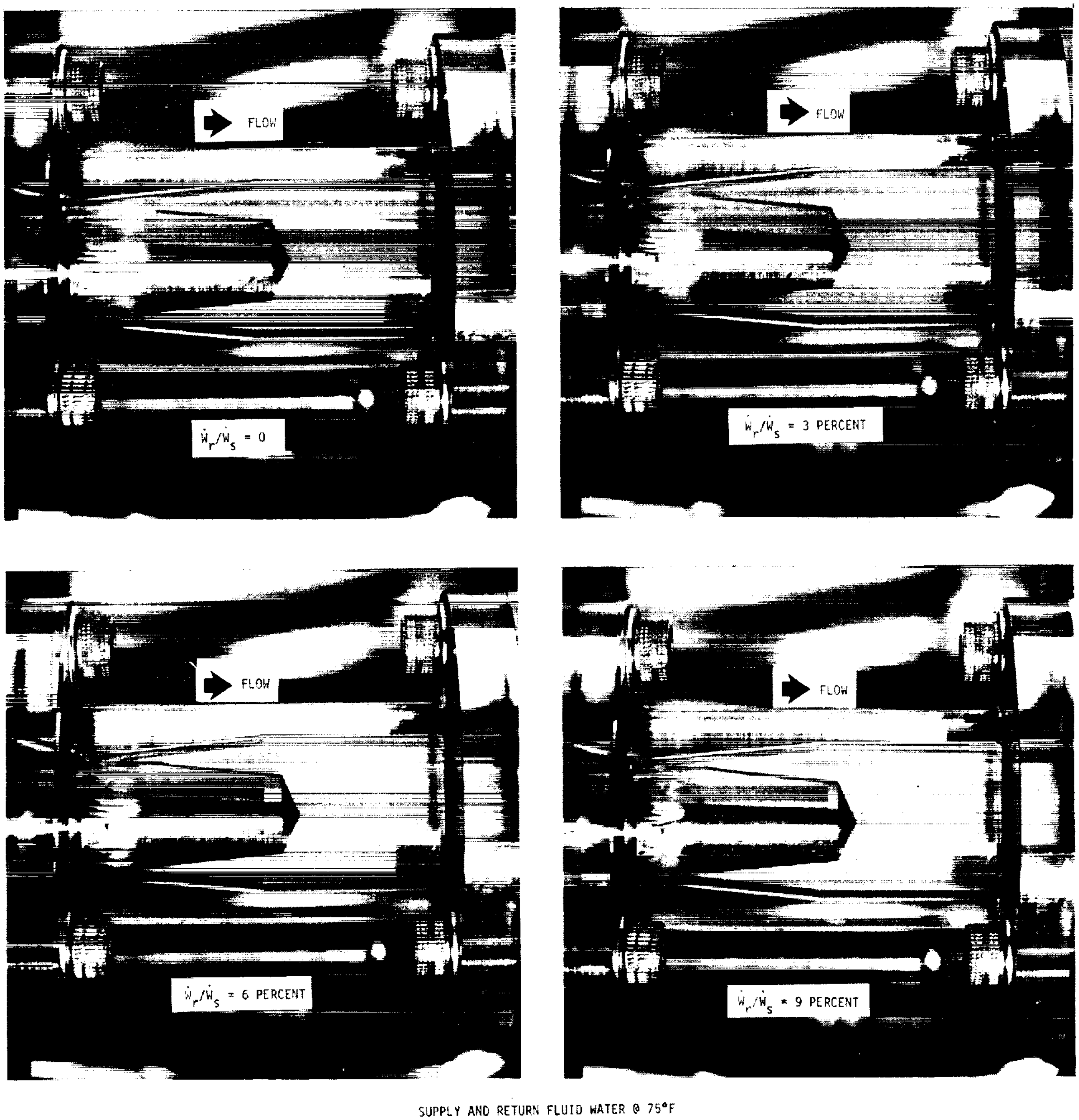


Figure 8-178. Return Flow in Venturi Sump (Pintle 37-1/2% in, Supply 200 psia 3.47 gpm, P_o/P_s= 0.25)

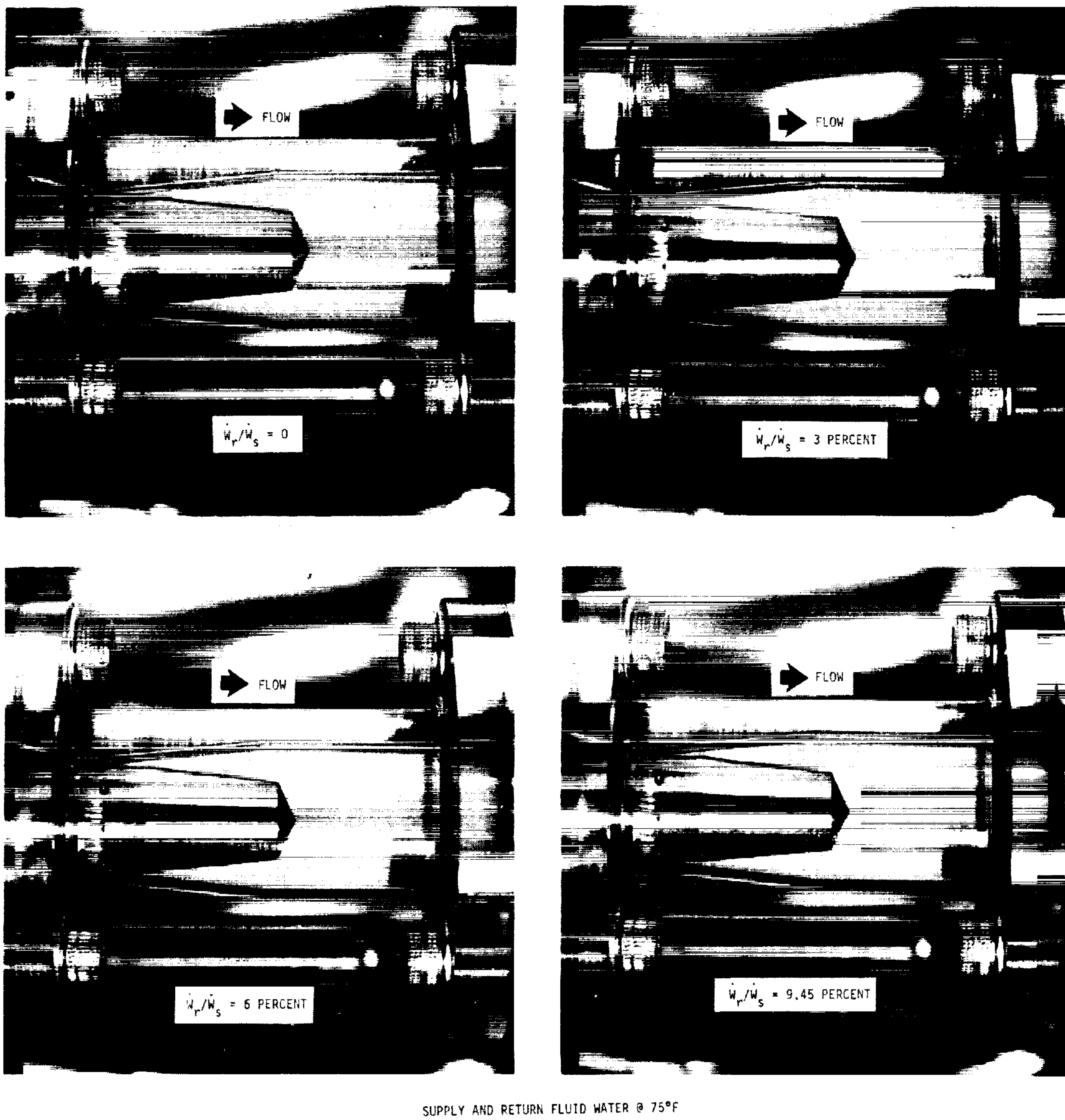


Figure 8-179. Return Flow in Venturi Sump (Pintle 37-1/2% in, Supply 200 psia 3.47 gpm, P_o/P_s= 0.5)

The current data does not reflect the ultimate return flow capability of the venturi sump, since the test return flows were limited by the available facility pressures. However, the initial testing did serve to prove out the venturi sump, which performed better than anticipated. The optimum axial position for the return flow orifices was also located. In addition, visual observations of the cavitation region has indicated a possible improvement of the sump by returning fluid flow through an annular slit rather than the eight equally spaced orifices.

8.7.6.5 Water Return Throttling Capability - The throttling characteristic of the venturi sump was also investigated utilizing a water supply of 100 psia and water to throttle through the return supply at several pintle positions and back pressures. The data taken at pintle positions of 12-1/2 percent in and 25 percent in are representative (Figures 8-180 and 8-181) in that throttling gain was considerably less than 1 and excessive fluid power is required to perform liquid-liquid throttling in the present configuration.

8.7.6.6 Gas Return Throttling Capability - Additional testing was also performed to determine the throttling capability of the venturi sump utilizing a water supply and nitrogen to throttle through the return supply. The throttling characteristic was investigated with a 100 psia supply at three pintle positions (full out, 12-1/2 percent in, and 25 percent in - minimum area) and at three back pressures, i.e., P_o/P_s = 0.2, 0.5 and 0.8 (see Figures 8-182, 8-183, and 8-184).

Maximum throttling occurred with the pintle in the full out position (i.e., with the return orifices 1/8 inch upstream of the throat) and throttling improved as the back pressure was increased. An important characteristic noted was that throttling of the initial 25 percent of the supply flow was accomplished with a gain of about 8, i.e., the water flow was throttled 8 times more than would be expected by the gas expansion alone. Initially, the supply flow at 100 psia was throttled 25 percent by a gas flowrate of 0.1 percent by weight, and 75 percent by a gas flowrate of 1 percent by weight. A comparison of the throttling characteristic at supply pressures of 100 and 200 psia are given in Figure 8-185. It should be noted that the throttling gains at 200 psia are roughly half of those at 100 psia.

The turbulence induced by the addition through the return of varying flowrates of nitrogen into the water supply of the venturi sump is shown in Figures 8-186 and 8-187. These photographs were taken with the water supply at 100 psia and a back pressure of 20 psia with the pintle at the full out and 12-1/2 percent in positions. Gas to water ratios of 0.016 percent by weight produced a high degree of turbulence and thorough mixing of the main stream. An annular return orifice should also provide a vast improvement in the performance of the venturi sump as a gas-liquid throttle.

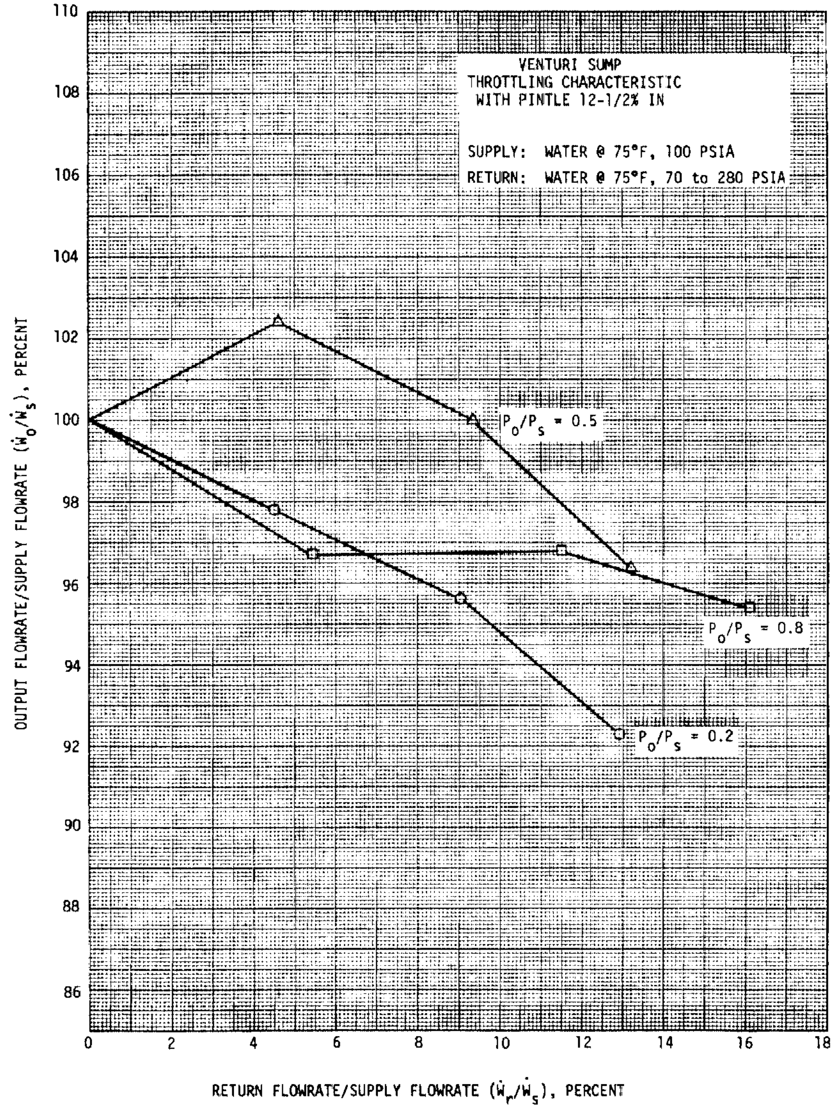


Figure 8-180

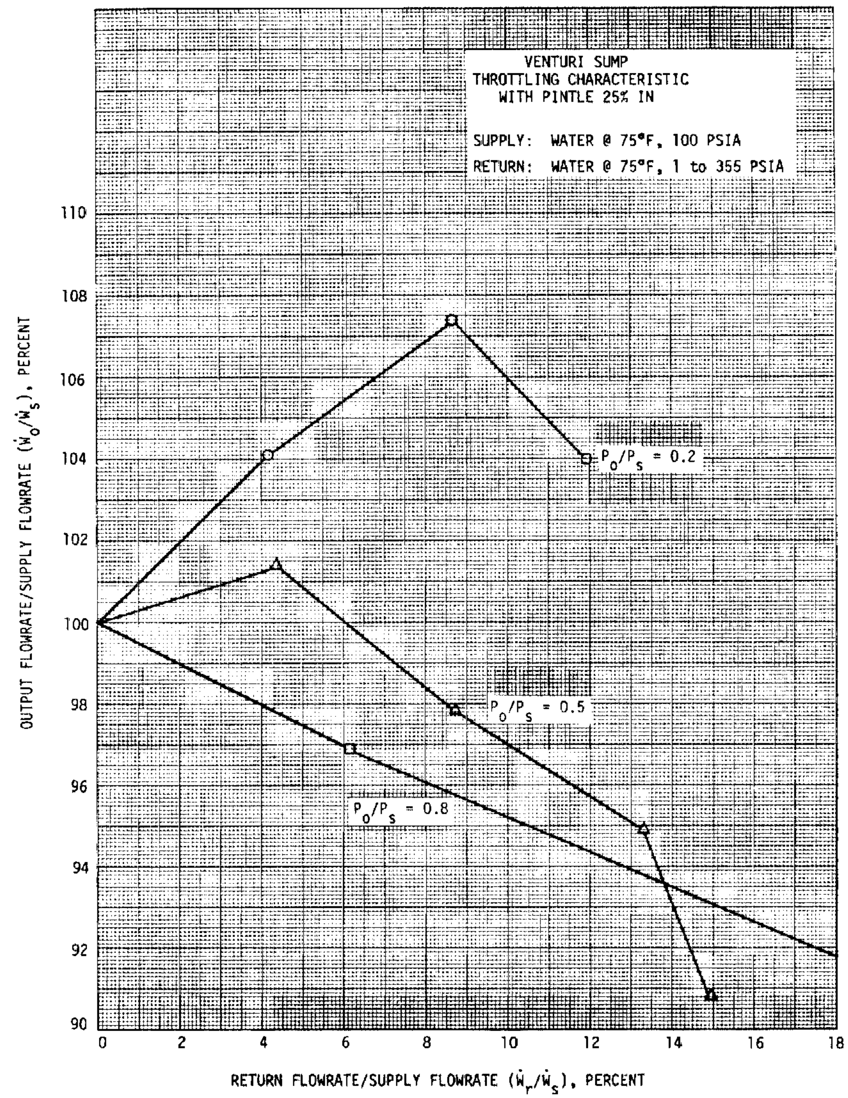


Figure 8-181

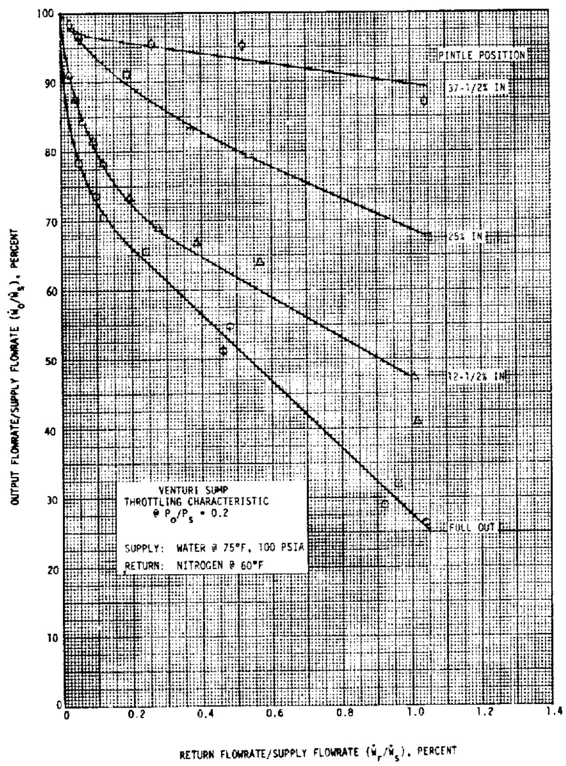


Figure 8-182

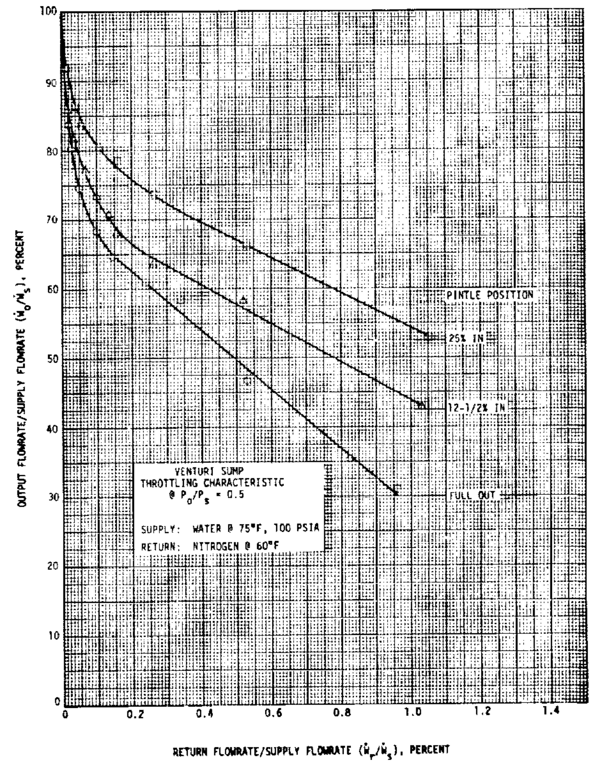


Figure 8-183

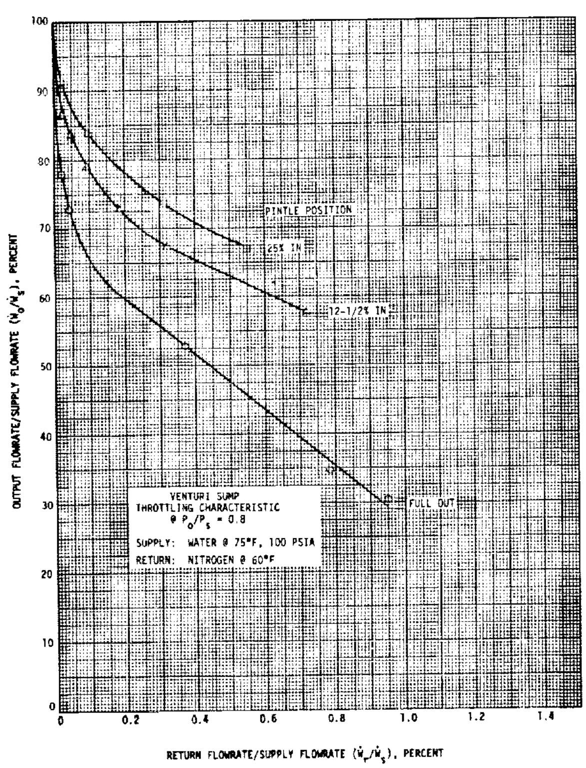


Figure 8-184

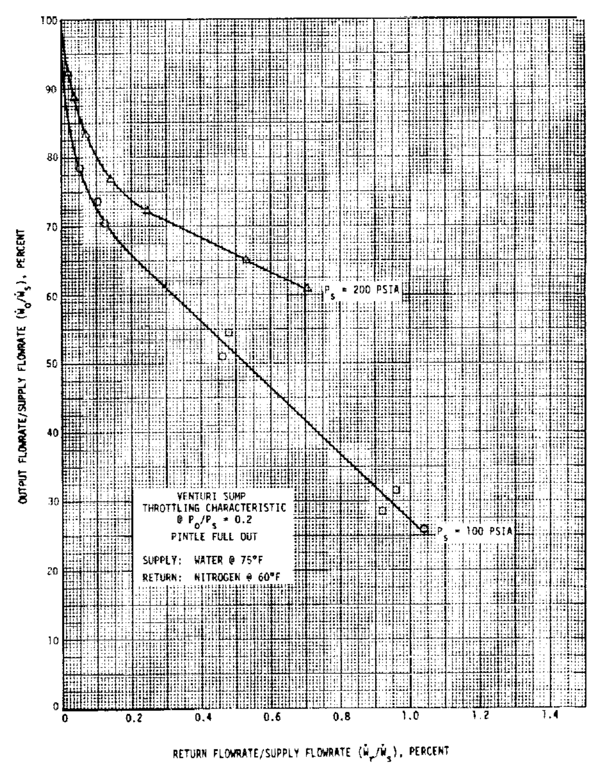


Figure 8-185

Figure 8-186. Nitrogen-Water Interaction in Venturi Sump (Pintle Full Out, P_o/P_s = 0.2)

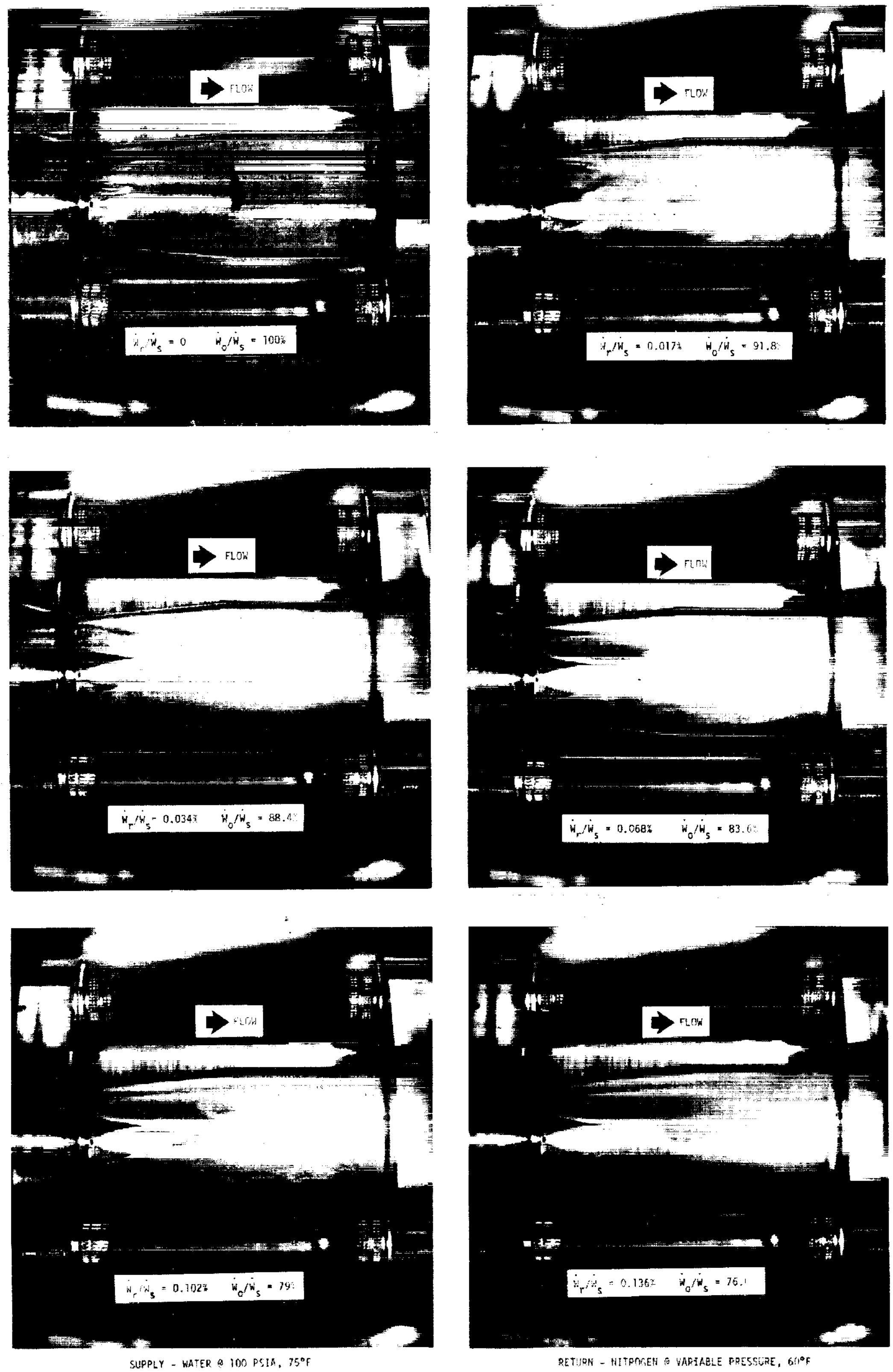


Figure 8-187. Nitrogen-Water Interaction in Venturi Sump (Pintle 12-1/2% in, P_o/P_s = 0.2)

8.7.6.7 Fluidic Control Demonstration - A fluidic proportional amplifier high gain block (Figure 8-188) was installed in a sealed enclosure (Figure 8-189) and then in the test setup of Figure 8-163. Preliminary testing was accomplished operating the fluidic amplifier with the vent exhausting to the return supply of the venturi sump. The initial test results were excellent, in that the differential output pressure, ΔP_o, of the fluid amplifier and the return flow to the sump (F.M. #2) remained constant at main supply pressures (P_s) of 135, 215, and 415 psia and throughout the entire cavitation regime. The fluidic amplifier was exercised several times at each supply pressure and at various cavitation levels. In all cases the fluidic amplifier functioned properly in that the gain and the output saturation level, ΔP_o maximum, was unchanged.

8.7.6.8 Summary - The feasibility of the venturi sump has been verified by the documentation of a total of 454 steady state operating points. A fluidic system was also successfully operated on water while venting to the venturi sump.

Excellent return flow capability was demonstrated. The optimum point appears to be just downstream of the throat section. Current water return flow capability with water supply ranges from 1 to 10 percent of the supply flow. Up to 2 percent nitrogen flow (limited by the test setup) by weight was also returned to a water supply. A large improvement appears possible by returning fluid through an annular slit rather than the eight equally spaced orifices.

High gain throttling of the cavitating water supply was obtained by injecting gaseous nitrogen through the return orifices upstream of the throat. Throttling of the initial 25 percent of the supply flow was accomplished with a gain of about 8, i.e., the water was throttled 8 times more than would be expected by gas expansion alone. About 75 percent of the initial supply flow was throttled by a gas flowrate of 1 percent by weight.

Important possible applications of the venturi sump include:

1. Constant pressure reference for space systems

2. Nonoverboard vent for fluidic systems

3. Fluidic propulsion controls - regulators, throttles, mixture ratio, SITVC

4. The combination and metering of reacting and nonreacting fluids in the chemical and food processing industries.

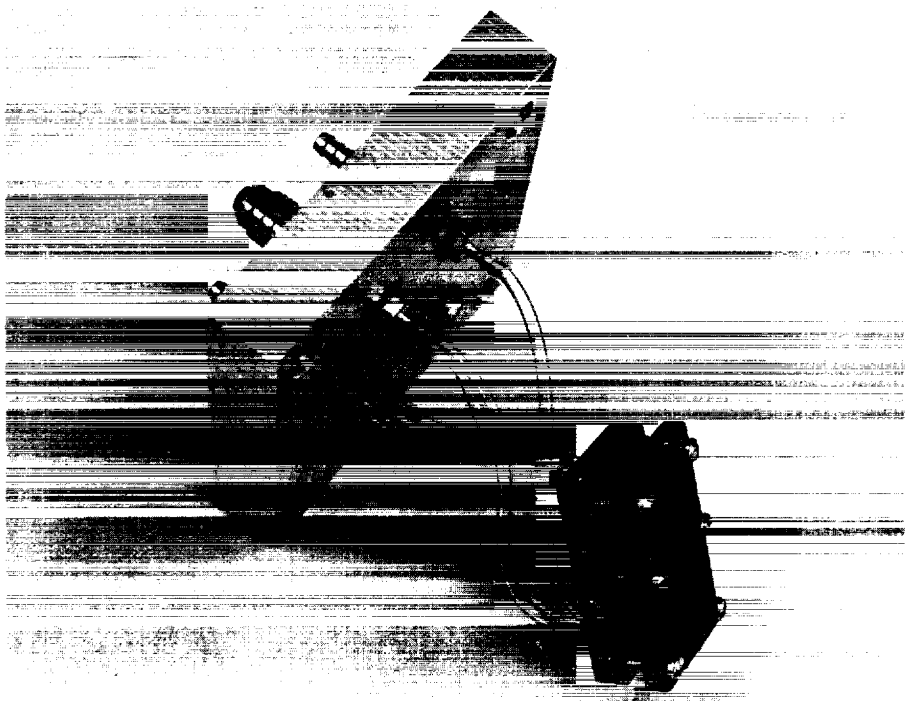


Figure 8-188. Fluidic Amplifier and Manifold Plate

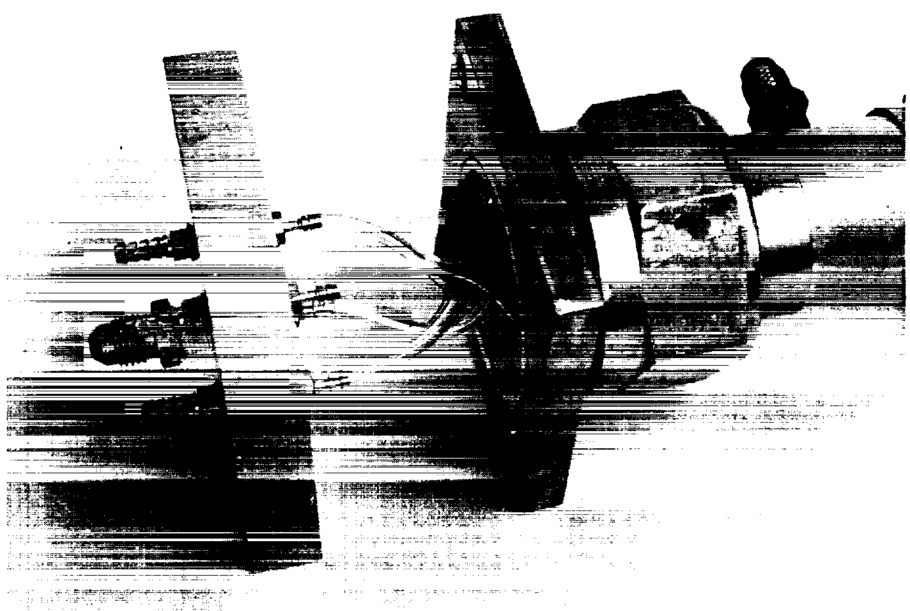


Figure 8-189. Fluidic Amplifier and Sealed Enclosure

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APPENDIX 8-A

FLUIDIC NOMENCLATURE AND UNITS

Basic Quantities

The quantities listed below are general; specific quantities should be identified by subscripts (e.g., P_{02} would be pressure at port 02).

Quantity	Nomenclature	Units (std)	Units (SI)*
Length	--	inch; in	(meter, m)
Force	F	pound, lb	(newton; N)
Mass	m	$lb\text{-}sec^2/in$	(kilogram; kg)
time	t	seconds; sec	(seconds; s)
angle	--	degrees; ^{o}	(radians; rad)
frequency	f	cycles/sec; cps	(hertz; H_z)
area	A	in^2	(m^2)
acceleration	a	in/sec^2	(m/s^2)
gravitational constant	g	in/sec^2	(m/s^2)
temperature, static	T	degrees Rankin; ^oR	(degrees Kelvin; ^oK)
temperature, total	T_o	^oR	^oK
velocity, angular	ω	rad/sec	(rad/s)
acceleration, angular	α	rad/sec^2	(rad/s^2)
volume	V	in^3	(m^3)
weight density	γ	lb/in^3	(N/m^3)
mass density	ρ	$lb\text{-}sec^2/in^4$	(kg/m^3)
weight flow rate	w	lb/sec	(N/s)

*System International Units

Quantity	Nomenclature	Units	
mass flow rate	$\dot{m}$	lb-sec/in	(kg/s)
volume flow rate	Q	in^3/sec	(m^3/s)
velocity, general	u	in/sec	(m/s)
velocity, mean	$\bar{u}$	in/sec	(m/s)
velocity, acoustic	u_c	in/sec	(m/s)
pressure, general	P	lb/in^2 or psi	(N/m^2)
pressure, absolute	P_a	psia	(N/m^2)
pressure, gage or drop	P_g	psig	(N/m^2)
power	W	lb in/sec	(Nm/s)
specific heat ratio	k	dimensionless	
absolute viscosity	μ	lb-sec/in^2	(N-s/m^2)
kinematic viscosity	ν	in^2/sec	(m^2/s)
liquid bulk modulus	β	lb/in^2	(N/m^2)
efficiency	η	dimensionless	
fluid impedance	Z	sec/in^2	(N-s/m^2-kg)
fluid resistance	R	sec/in^2	(N-s/m^2-kg)
fluid capacitance	C	in^2	(kg-m^2/N)
fluid inductance	L	sec^2/in^2	(N-s^2/kg-m^2
Mach number	M	dimensionless	
Laplace operator	s	1/sec	(1/s)
pressure gain	G_P	dimensionless	
flow gain, average	G_F	dimensionless	

Quantity	Nomenclature	Units
flow gain, incremental	G_{Fi}	dimensionless
power gain, average	G_P	dimensionless
power gain, incremental	G_{Pi}	dimensionless
signal - noise ratio	S/N	dimensionless

General Subscripts

control	c
output	o
supply	s
control, quiescent	co
control differential	cd
output differential	od

APPENDIX 8-B

FLUIDIC TERMINOLOGY LIST

APPENDIX 8-B
FLUIDIC TERMINOLOGY LIST

ACTIVE	Adjective to describe an amplifying or switching device whose operation depends upon a separate supply source of power.
ACTUATOR	A component device or system which provides a mechanical actuation in response to some input signal.
AMPLIFIER	An active device or component which provides a variation in output signal having a potential power level variation which is usually greater then that of the impressed input control signal variation.
ANALOG	Adjective to describe a general class of components or circuits in which all signals may vary continuously (as opposed to signals which may only vary in discrete increments).
ASPECT RATIO, NOZZLE	Ratio of nozzle depth to nozzle width. (Relative to a two dimensional element.)
BANDWIDTH	The operating frequency range of a device as defined by the minimum (usually zero or steady state) and maximum operating frequencies. An indication of maximum operating frequency is the frequency at which the output signal lags the control signal by 45 degrees for a specified load and control amplitude.
BIAS	Magnitude of input signal to null or provide zero output signal for differential amplifiers; signal magnitude required to establish operating point for single-ended amplifiers.
BOUNDARY LAYER AMPLIFIER	An amplifier which utilizes the separation-point control of a power stream from a curved or plane surface to modulate the output.
CAPACITOR	A passive fluid element which produces a pressure within itself which lags the inflow rate by 90 degrees phase.

CIRCUIT	An array of interconnected components and elements which performs a desired function; for example, an integrator, counter, or operational amplifier.
CLOSED AMPLIFIER	A fluidic amplifier which has no communication with an independent reference; i.e., the interaction region is not vented.
DIGITAL	The general class of devices or circuits whose output is a discontinuous function of its input.
ELEMENT	The general class of devices in their simplest form, used to make up fluidic components and circuits; for example, resistors, capacitors, flip-flops, and jet deflection amplifiers.
FAN-IN	The number of control signals (push-pull or single ended) accepted by a logic gate, which can affect the desired change in state of the logic gate.
FAN-OUT	The number of components which can be driven by a single component; all components are to be operated at the same supply pressure. Also, components are to be of similar size and have similar switch points. Fan-out value relates to steady-state operation unless the corresponding frequency is given.
FLIP-FLOP	A bistable flueric component (reset-set) which changes state with the proper reset-set input of sufficient amplitude and width. It exhibits "memory" (remains in a particular state) once it has switched, without requiring a continual input signal.
FLOW AMPLIFIER	An amplifier designed primarily for amplifying flow signals.
FLOW RECOVERY, OUTPUT	The maximum output mass-flow rate divided by the supply mass-flow rate. Generally given as a percentage.
FLUERIC	An adjective sometimes applied to those fluidic components and systems which perform sensing, logic, amplification, and control functions, but which use no moving mechanical elements whatsoever to perform the desired function.

FLUERICS	The area within the field of fluidics in which fluid components and systems perform sensing, logic, amplification, and control functions without the use of moving mechanical parts.
FLUIDIC	An adjective denoting a device or system in which some sensing, control, signal processing, and/or amplification functions are performed through the use of fluid dynamic phenomena (no moving mechanical parts).
FLUIDIC COMPONENT	A fluidic device, distinguished from an element by virtue of the fact that it is composed of more than one element.
FLUIDICS	The general field of fluid devices and systems and the associated peripheral equipment used to perform sensing, logic, amplification, and control functions.
FOCUSED JET AMPLIFIER	An amplifier which utilizes control of the attachment of an annular jet to an axisymmetric flow separator, (that is, control of the focus of the jet) to modulate the output.
FREQUENCY RESPONSE	Usually given in the form of frequency response curves of the variation of output/input amplitude ratio and phase as a function of frequency.
GAIN, FLOW (ANALOG)	Average gain; the slope of a straight line drawn through an input flow versus output flow curve, so that deviations from the measured curve up to the maximum output level are minimized. Deviations should be based on net area. If other than maximum output level is used for the average gain definition, the range should be noted. Measured curve is to be for either low output pressure recovery (resulting from instrumentation) or a value which provides maximum flow gain.
GAIN, FLOW (DIGITAL)	Ratio of output flow change to input flow change (from quiescent) required for switching to occur.
GAIN, FLOW (INCREMENTAL, ANALOG)	The slope of the output flow versus the input flow curve at the operating point of interest.

GAIN, POWER (ANALOG)	Average power gain; ratio of the change in output power to the change in input power; the average value over operating range up to maximum output level unless the range is stated.
GAIN, POWER (DIGITAL)	Ratio of the change in output power to the change in input power (from quiescent) for switching to occur.
GAIN, POWER (INCREMENTAL, ANALOG)	The slope at the operating point of an input/output power curve.
GAIN, PRESSURE (ANALOG)	Average gain; the slope of a straight line drawn through a measured input pressure versus output pressure curve so that deviations from the measured curve up to the maximum output level are minimized. Deviations should be based on net area. If other than the maximum output level is used for the average gain definition, the range used should be noted. Gage pressure values should be used. The measured curve is to be for either zero output flow or a value which provides maximum pressure gain (see Figure 8-B1).
GAIN, PRESSURE (INCREMENTAL, ANALOG)	Incremental gain; the slope of the measured input pressure versus output pressure curve at the operating point of interest (see Figure 8-B1).
GAIN, PRESSURE (DIGITAL)	Ratio of measured output pressure change to input pressure change (from quiescent) required for switching to occur. All control ports except the one under consideration should be maintained at the quiescent pressure level. Output flow should be zero or a value which results in maximum pressure gain. If gain value is for other than steady-state conditions, the test frequency should be stated.
HYDRAULIC DIAMETER	The ratio of the cross-sectional area of a flow passage to one-fourth the wetted perimeter of the passage.
HYSTERESIS, ANALOG AMPLIFIER	Total width of hysteresis loop expressed as a percent of peak-to-peak saturation input signal. Measurements must be at frequencies below those where dynamic effects become significant (see Figure 8-B2). Measurements to be made at the widest point on the curve.

HYSTERESIS, DIGITAL AMPLIFIER	Width of the hysteresis loop as measured on an input/output curve and expressed as a percentage of the supply conditions; for example flow hysteresis is the hysteresis-loop width (measured on an input/output flow curve), divided by the supply flow (see Figure 8-B3).
IMPACT MODULATOR	An amplifier which utilizes the control of the intensity of two directly opposed, impacting power jets thereby controlling the position of the impact plane to modulate the output.
IMPEDANCE, INPUT	The ratio of pressure change to flow change measured at an input port. Numerical value may depend on operating point, since input pressure-flow curve may not be linear. For active elements, the power source should be connected for measurements.
IMPEDANCE, OUTPUT	The ratio of pressure change to flow change, measured at an output port. Numerical value may depend on operating point, since output pressure-flow curve may not be linear.
INDUCTOR	A passive flueric element which, because of fluid inertance, has a pressure drop across it which leads the through flow by 90 degrees phase.
JET-DEFLECTION AMPLIFIER (ALSO BEAM-DEFLECTION OR STREAM INTERATION AMPLIFIER)	An amplifier which utilizes control ports to deflect a power jet and modulate the output. Usually employed as an analog amplifier.
LINEARITY DEVIATION, OUTPUT	Deviation of the measured curve from the straight-line average gain approximation: The ratio of the deviation to the peak-to-peak output range (range should be stated if other than maximum output level) expressed as a percentage (see Figure 8-B4).
LOGIC ELEMENTS (ALSO LOGIC GATES)	The general category of digital components which provide logic functions; for example, AND, OR, NOR, and NAND. They can gate or inhibit signal transmission with the application, removal, or other combinations of input signals.
MEMORY	The capability of a logic gate to retain the state of its output signal corresponding to the most recently applied control signal after the control signal is removed.

PASSIVE	The general class of devices which operate on the signal power alone.
POWER AMPLIFIER	An amplifier designed primarily to provide maximum power gain.
PRESSURE AMPLIFIER	An amplifier designed primarily to amplify pressure signals.
PRESSURE RECOVERY, OUTPUT	The difference between the maximum output pressure and the local vent pressure divided by the difference between the supply pressure and the pressure in the interaction region. For closed amplifiers, the control port pressure should be used as the reference pressure.
RESISTOR	A passive fluidic element which, because of viscous losses, produces a pressure drop as a continuous function of the flow through it.
RESPONSE TIME	The time interval between the application of an input step signal and the resulting output signal. The time measurement for the response to the input step signal is to be made when the output signal reaches a level which is 63 percent of the final output value (see Figure 8-B5).
REYNOLDS NUMBER	A dimensionless parameter of fluid flow which often indicates the ratio of inertial-to-viscous forces: $N_R = \frac{\bar{u} d_h}{\nu}$ where d_h = hydraulic diameter, $\bar{u}$ = mean velocity of the fluid, and ν = kinematic viscosity.
SI	An abbreviation indicating the international system of units.
SATURATION	The maximum output value regardless of input magnitude (see Figure 8-B6).
SENSOR, FLUIDIC	A fluidic device which senses a basic quantity such as rate, position, acceleration, pressure, or temperature, in terms of a fluid quantity such as pressure or flow-rate.

SIGNAL-TO-NOISE RATIO (SNR) (ANALOG AMPLIFIER) — Ratio of maximum (saturation value) output signal amplitude to maximum noise amplitude (at output). Signal and noise data should be RMS values.

SIGNAL-TO-NOISE RATIO (DIGITAL AMPLIFIER) — Ratio of the amplitude of the output signal to the peak-to-peak maximum noise signal. Maximum noise signal is to be measured when the port is active and inactive. The greater value of the two is used in calculating the SNR.

TIME DELAY — The time from the initiation of an input signal until the first discernible change in the output, caused by this input signal (see Figure 8-B5).

TRANSPORT DELAY — Time required for a fluid particle to travel from the input control port region to the output receiver region.

TRUTH TABLE — A table depicting the function of a logic element; all possible combinations of input signals are tabulated along with the corresponding state of the output signal.

TURBULENCE AMPLIFIER — An amplifier which utilizes control of the laminar-to-turbulent transition of a power jet to modulate the output.

VENTED AMPLIFIER — A fluidic amplifier which utilizes vents to establish a reference pressure in the interaction region.

VORTEX AMPLIFIER — An amplifier which utilizes the pressure drop across a controlled vortex for modulating the output.

WALL ATTACHMENT AMPLIFIER — An amplifier which utilizes control of the attachment of a free jet to a wall (Coanda effect) to modulate the output. Usually employed as a digital amplifier.

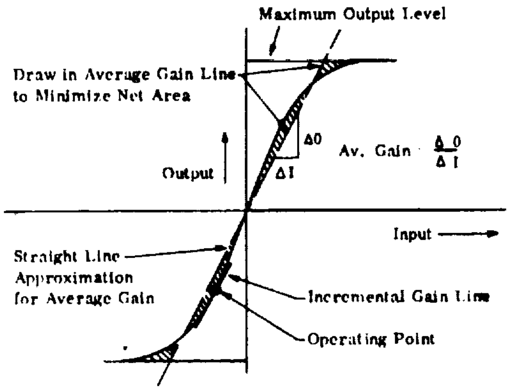


Figure 8-B1. Pressure Gain

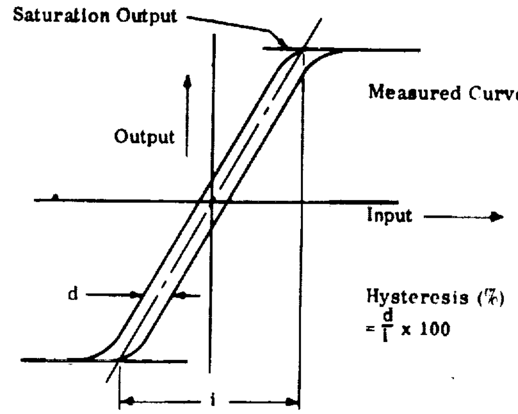


Figure 8-B2. Analog Amplifier Hysteresis

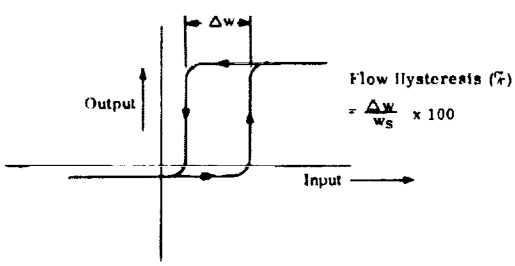


Figure 8-B3. Digital Amplifier Hysteresis

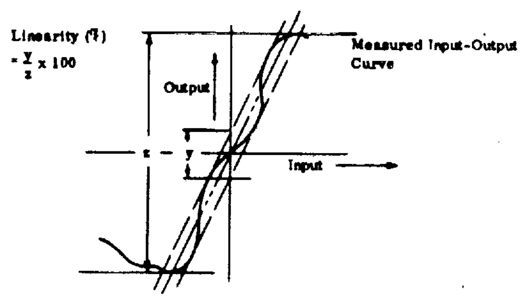


Figure 8-B4. Output Linearity

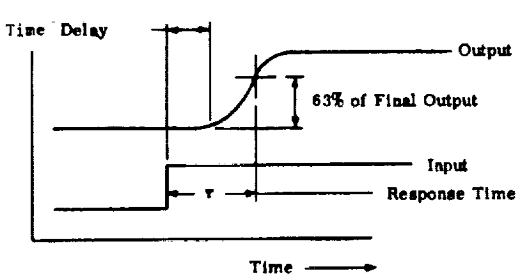


Figure 8-B5. Response Time and Transport Delay

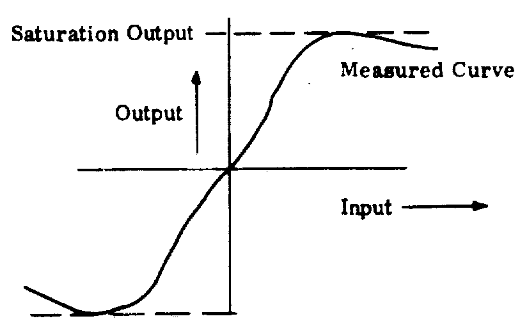


Figure 8-B6. Saturation

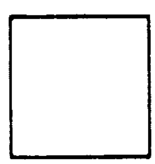
APPENDIX 8-C

FLUIDIC GRAPHICAL SYMBOLS

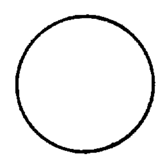
The purpose of the graphic symbols is to enable the circuit designer to employ meaningful and specific symbols in drawings and schematics which will clearly define the function or type of device employed to perform that function.

In the course of preparing this document, it was recognized that fluidic symbols were required to satisfy two basic needs. The first was the need of the system designer interested primarily in the <u>function</u> of the device. The second was the circuit designer primarily interested in the <u>operating principle</u> of the device.

The following is an integrated set of symbology which satisfies both requirements. Functions of the devices are defined by symbols enclosed within square envelopes. Operating principles of the devices are defined by symbols enclosed within round envelopes. The difference in envelopes is specifically intended to emphasize the difference in purpose of the symbols as shown below:



Functional
Symbol



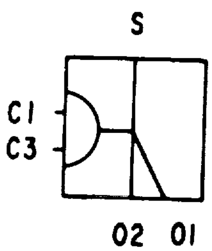
Operating Principle
Symbol

By definition, the symbols are intended to show the following:

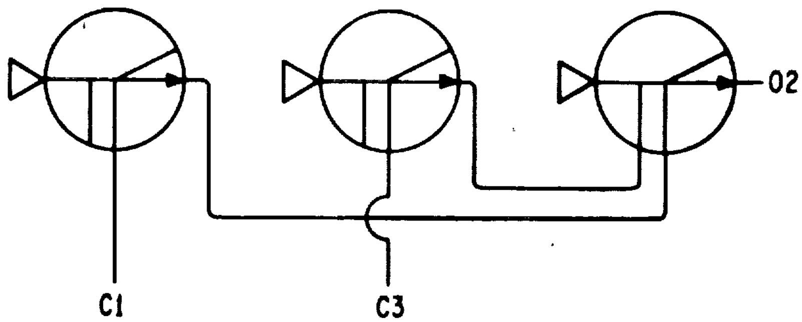
- Functional symbol – Depicts a function which may be performed by a single fluidic element or by an interconnected circuit containing multiple elements.
- Operating principle symbol - Depicts the fluid phenomena in the interaction region which is employed to perform the function as well as the function of the fluidic element.

In the cases where no operating principle is shown, it is implied that, at present, no <u>single</u> operating principle or interaction region is adequate to perform the function. In these cases a combination of operating principles or interaction regions is required to represent the function.

To further emphasize this point, consider the case of a 2-input AND made up from OR-NORs as follows:



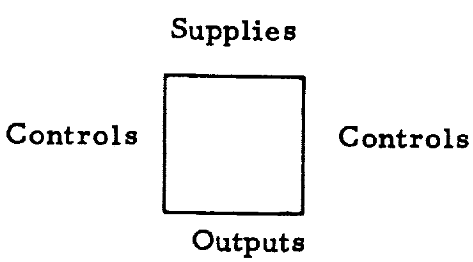
Functional
Symbol

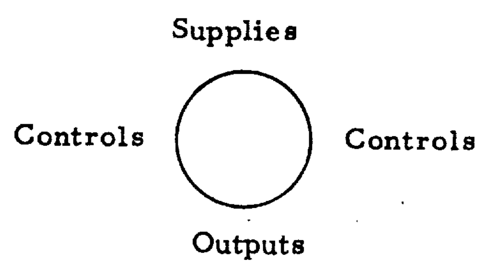


Interconnection of
Operating Principle Symbols

General Conventions

(a) The relative port locations for the symbols are patterned in the following manner:





All symbols may be oriented in 90-degree increments from the position shown.

(b) Specific ports are identified by the following nomenclature:

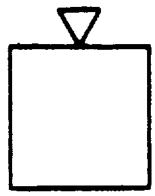
Supply port - S

Control port - C

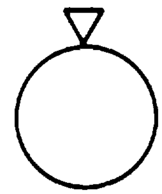
Output port - O

The nomenclature shown on the graphic symbols need not be used on schematic diagrams. It is primarily intended to correlate the function of each port with the truth table.

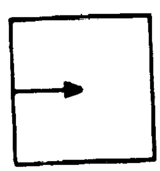
(c) Supply ports can be either active or passive. An inverted triangle, ∇, denotes a supply source connected to the supply port (active device).

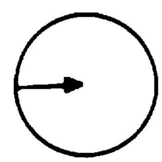


Active Devices



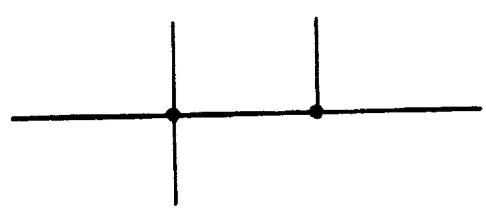
(d) An arrowhead on the control line inside the symbol envelope indicates continual flow is required to maintain state (no memory, no hysteresis):



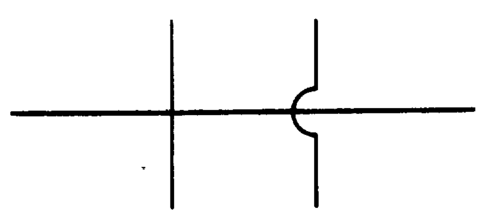


Indicates no memory

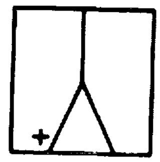
(e) Interconnecting fluid lines shall be shown with a dot at the point of interconnection:

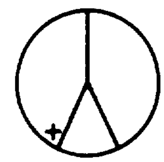


Crossing fluid lines are to be shown without dots:



(f) A small + on the output of a bistable device indicates initial or start-up flow condition.





(g) Logic Notation

A . B ≡ A "and" B

A + B ≡ A "or" B

$\overline{A}$. $\overline{B}$ ≡ "not" A and "not" B

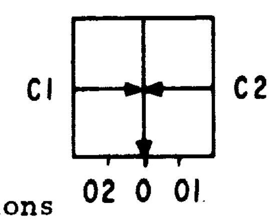
(h) Port Marking

Port nomenclature shown on schematics need not be used on schematic diagrams; the nomenclature may be useful, however, in correlating test data and specification data with the physical device.

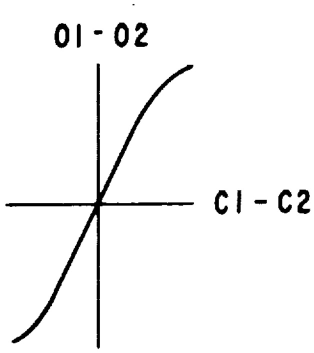
<u>Analog Fluidic Devices</u>

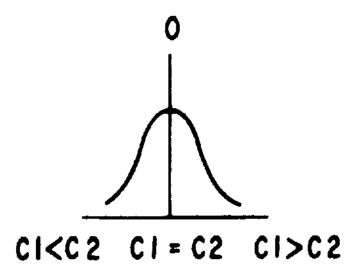
(a) Proportional Amplifiers

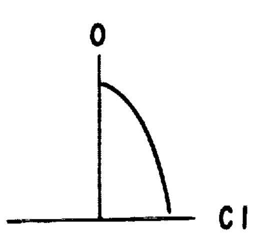
Functional Symbol

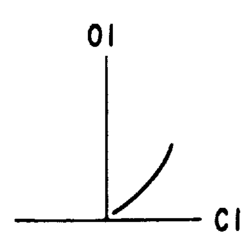


Functions

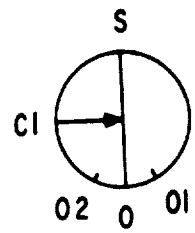




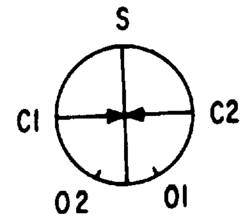




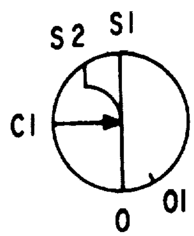
Operating Principle Symbols



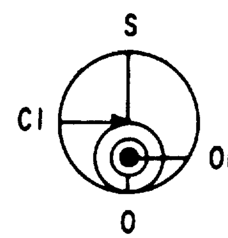
Single Input
Jet Interaction



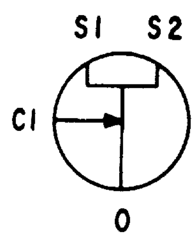
Differential
Jet Interaction



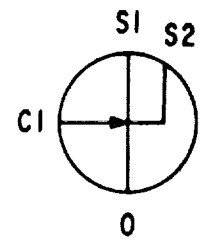
Separation
Point Control



Vortex



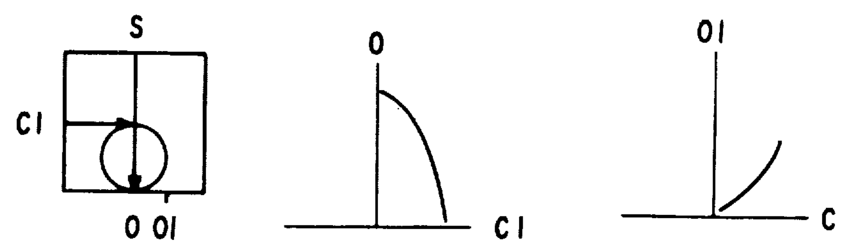
Transverse
Impact Modulator



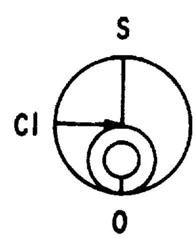
Direct
Impact Modulator

(b) Throttling Valve

Functional Symbol



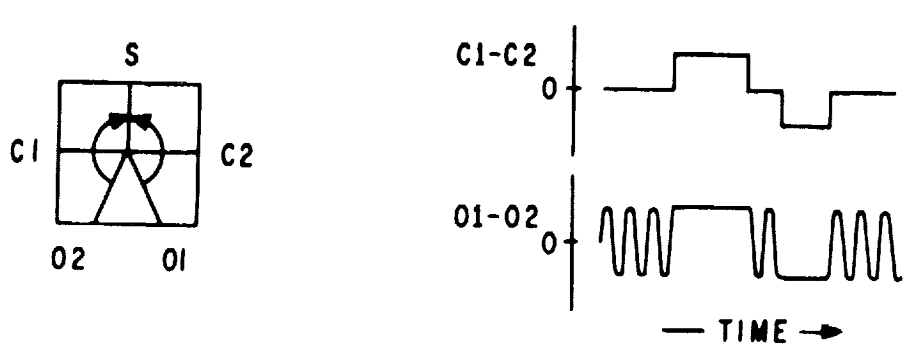
Operating Principle Symbol



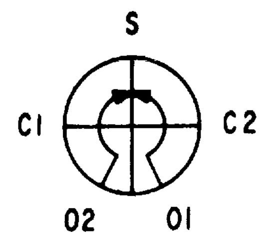
Vortex

(c) Oscillator (Sine Wave)

Functional Symbol

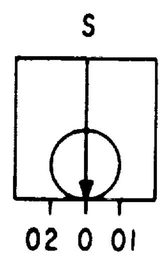


Operating Principle Symbol

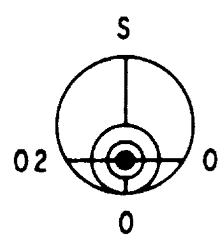


(d) Rate Sensor

Functional Symbol



Operating Principle Symbol

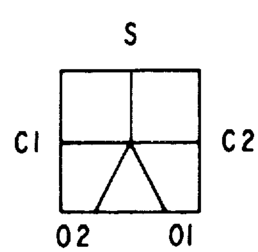


Vortex

Bistable Digital Devices

(a) Flip Flop

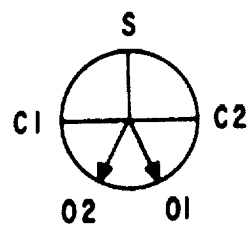
Functional Symbol



Truth Table

C1	C2	O1	O2
1	0	1	0
0	0	1	0
0	1	0	1
0	0	0	1

Operating Principle Symbols



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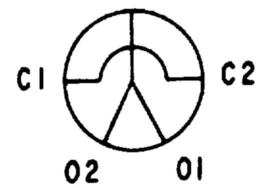
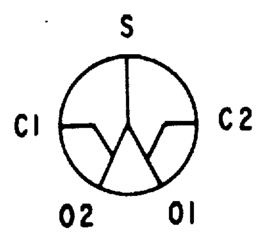


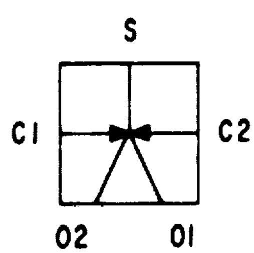
Edgetone



Induction

(b) Digital Amplifier

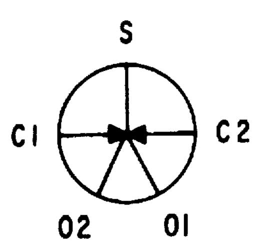
Functional Symbol



Truth Table

C1	C2	O1	O2
1	0	1	0
0	1	0	1
0	0	Undefined	
1	1	Undefined	

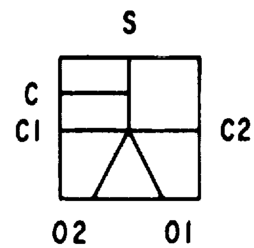
Operating Principle Symbol



Jet Interaction

(c) **Binary Counter**

Functional Symbol

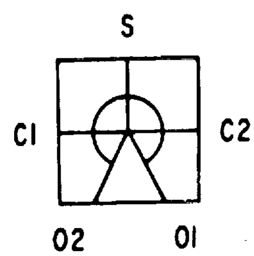


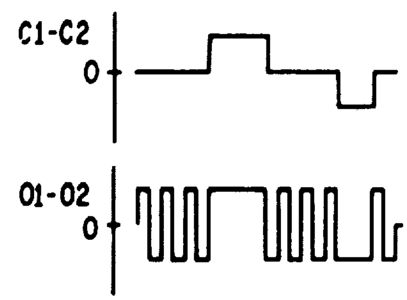
Truth Table

C	C1	C2	O1	O2
0	1	0	1	0
0	0	0	1	0
0	0	1	0	1
0	0	0	0	1
1	0	0	1	0
0	0	0	1	0
1	0	0	0	1
0	0	0	0	1

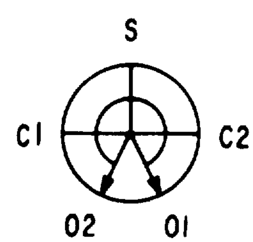
(d) **Multivibrator**

Functional Symbol





Operating Principle Symbol

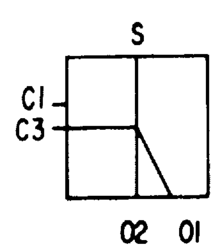


Wall Attachment

Monostable Digital Devices

(a) OR-NOR

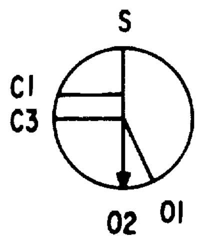
Functional Symbol



Truth Table

C1	C3	O1	O2
0	0	0	1
1	0	1	0
0	1	1	0

Operating Principle Symbols



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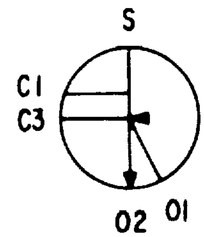
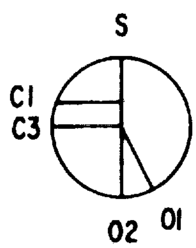
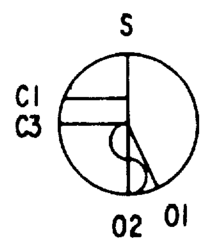


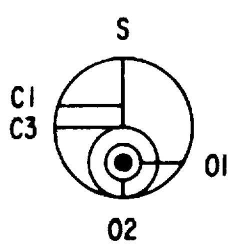
Wall Attachment
Internal Fluid Bias



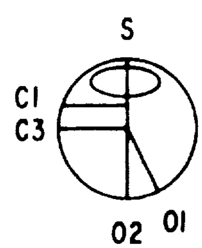
Jet Interaction
Geometrical Bias



Turbulence



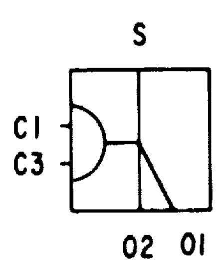
Vortex



Focused Jet

(b) AND-NAND

Functional Symbol

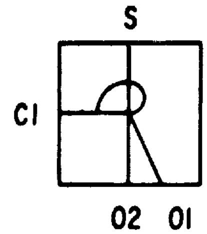


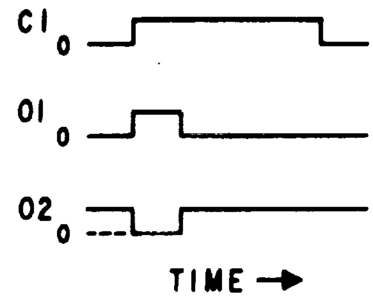
Truth Table

C1	C3	O1	O2
0	0	0	1
1	0	0	1
0	1	0	1
1	1	1	0

(c) **One-Shot**

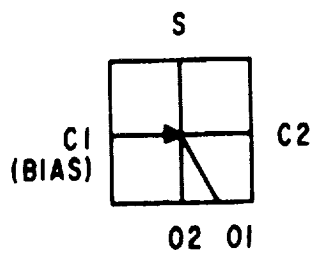
Functional Symbol





(d) **Schmitt Trigger**

Functional Symbol

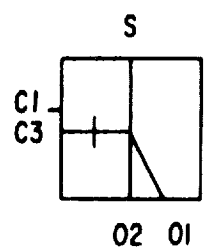


Truth Table

	O1	O2
C1 > C2	1	0
C1 < C2	0	1
C1 = C2	Undefined	

(e) **Exclusive OR**

Functional Symbol



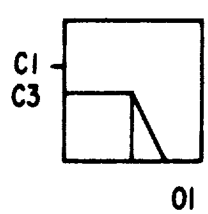
Truth Table

C1	C2	O1	O2
0	0	0	1
1	0	1	0
0	1	1	0
1	1	0	1

Passive Digital Devices

(a) **OR**

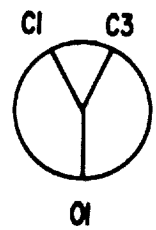
Functional Symbol



Truth Table

C1	C3	O1
0	0	0
1	0	1
0	1	1
1	1	1

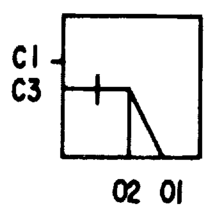
Operating Principle Symbols



Passive
Jet Interaction

(b) Exclusive OR-AND

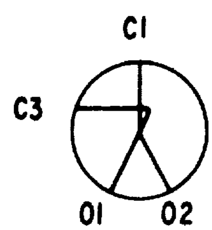
Functional Symbol



Truth Table

C1	C3	O1	O2
1	0	1	0
0	1	1	0
1	1	0	1
0	0	0	0

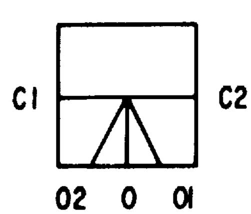
Operating Principle Symbols



Passive
Jet Interaction

(c) AND - 2/3 AND

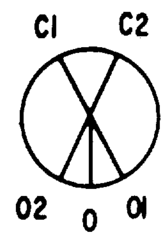
Functional
Symbol



Truth Table

C1	C2	O1	O2	O
1	0	1	0	0
0	1	0	1	0
1	1	0	0	1
0	0	0	0	0

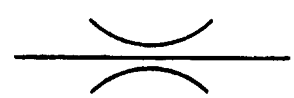
Operating Principle Symbols



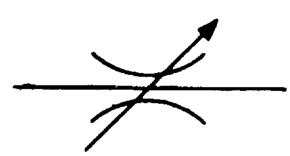
Passive
Jet Interaction

Fluidic Impedances

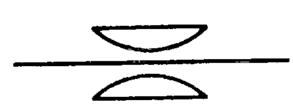
(a) General Resistance - Fixed



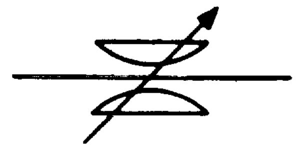
(b) General Resistance - Variable



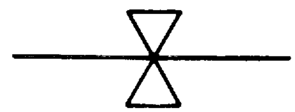
(c) Linear Resistance - Fixed



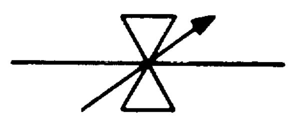
(d) Linear Resistance - Variable



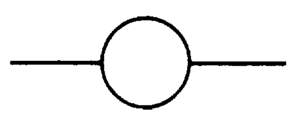
(e) Nonlinear Resistance - Fixed



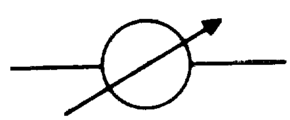
(f) Nonlinear Resistance - Variable



(g) Capacitance - Fixed

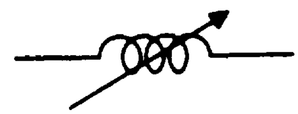


(h) Capacitance - Variable

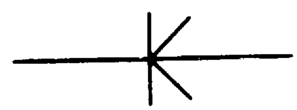


(i) Inductance - Fixed

(j) **Inductance - Variable**



(k) **Diode**



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